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Frontispiece and Guest Editorial . . . . . *Rawson Bennett* 1, 2

Spacious Fantasies . . . . . *John R. Pierce* 3

Microwaves in the Space Age . . . . . *H. Richard Johnson* 5

The Role of Radar in Space Research . . . . . *K. J. Craig, A. Shapiro and B. S. Yaplee* 11

A Radio-Astronomy Project at the University of Illinois . . . . . *George C. McVittie* 14

High-Altitude Measurements of X Rays and Far Ultraviolet Radiation . . . . . *Herbert Friedman* 18

A Gas Cell "Atomic Clock" as a High-Stability Frequency Standard . . *Maurice Arditi* 25

Precision Optical Tracking of Artificial Satellites . . . . . *W. F. Hoffmann, R. Krotkov and R. H. Dicke* 28

Field Emission, A Newly Practical Electron Source . . . . . *W. P. Dyke* 38

The ONR Program in the Electronics Research Laboratory of the University of California, Berkeley . . . . . *Samuel Silver* 46

Communication Using Earth Satellites . . . . . *Jerome B. Wiesner* 51

Contributors 58

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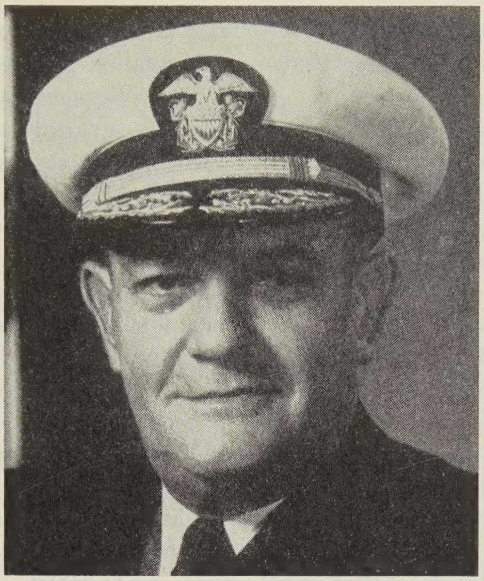

Rear Admiral Rawson Bennett II

Rawson Bennett II (A'36–M'43–SM'43–F'50) was born in Chicago, Ill., on June 16, 1905. He was graduated from the U. S. Naval Academy, Annapolis, Md., in 1927 with the commission of Ensign. He subsequently advanced to the rank of Captain in 1945, and was appointed Rear Admiral in 1955.

From 1927 until 1934, he served on various ships of the Fleet, including *U.S.S. California, U.S.S. Isabel, U.S.S. Rochester, U.S.S. Houston,* and *U.S.S. Idaho.* In 1934, he returned to the Naval Academy for postgraduate instruction in radio (electronic) engineering, and later received the M.S.E.E. degree from the University of California, Berkeley. While still on sea duty, he set up the technical program of the first Fleet Sound School at San Diego, Calif.

In 1941, he reported to the Bureau of Ships, Navy Department, Washington, D.C., where he served first as Head of the Underwater Sound Design Section of the Radio Division, and as Head of the Electronics Design Division from 1943 to 1946. He was awarded the Legion of Merit "for exceptionally meritorious conduct" during his tour of duty with the Bureau of Ships.

In 1946, he reported as Director of the U. S. Navy Electronics Laboratory, Point Loma, San Diego, Calif., where he set up the post-war expansion of that laboratory. In 1950, he was ordered to Washington, D.C., where he set up and became the first Director of the Electronics Production Resources Agency of the Departments of the Army, Navy, and Air Force. In 1951, he was assigned duty in the Bureau of Ships as Head of the Mine Warfare Branch. He next served, in 1953, as Naval Inspector of Ordnance at General Electric Company, Schenectady, N.Y. In 1954, he again served in the Bureau of Ships as Assistant Chief of the Bureau for Electronics.

In December, 1955, with the rank of Rear Admiral, he was appointed Chief of Naval Research, to which post he was reappointed in 1959.

In addition to the Legion of Merit, he has also received the Yangtze Service Medal, the American Defense Service Medal, the Fleet Clasp, the American Campaign Medal, the World War II Victory Medal, and the National Defense Service Medal.

Rear Admiral Bennett is a Fellow of the Acoustical Society, the AIEE and the American Association for the Advancement of Science. He is a registered professional engineer in the state of California.

Space Electronics in the Navy

THIS ISSUE of the IRE TRANSACTIONS ON MILITARY ELECTRONICS is devoted to the United States Navy's interest and effort in space electronics.

It is entirely appropriate to compile, in this scientific journal, a representative indication of Naval research under way, leading to solutions of the many problems which confront designers, controllers, trackers and potential users of extraterrestrial vehicles of the present and future.

The Navy does have a special role in space—a role which is a direct outgrowth of its all-important task of controlling the sea lanes. The Navy has publicly stated its aim to use space for the accomplishment of naval objectives, and also to be able to prevent enemies from using space as a barrier against attaining those objectives. Toward this end, the Navy Department has been developing its own program of space technology, utilizing the basic sciences in all related areas to achieve added naval capabilities through the use of space techniques. This program is largely an extension of a broad program of basic and applied research in whose stimulation and support the Navy Department has traditionally taken the lead, and which was vigorously intensified after World War II.

The Navy has unique requirements in the need for precision navigation of surface and subsurface ships. It has singular needs in methods and equipment to insure reliable communications among widely separated fleet units, patrolling submarines and polar-based operating elements. It looks to space technology to assure that its mission can be accomplished effectively.

Since 1946, the Office of Naval Research has joined with Army Signal Corps and the Air Force Office of Scientific Research in support of large academic laboratories of research in physical electronics. Included in this program are the Research Laboratory of Electronics, Massachusetts Institute of Technology, Division of Applied Science and Engineering, Harvard University, Electronics Research Laboratories, Stanford University, and Microwave Research Laboratory, Polytechnic Institute of Brooklyn. In addition to the three-service sponsorship, there are many other Navy-supported tasks at academic and industrial electronics laboratories.

At these centers, the best scientific and engineering talent of the country has been engaged in advancement of the electronics art. Out of the effort have come many of the techniques and devices which space technology requires, as for instance, radio wave propagation data and theory, microcircuitry analysis and synthesis, solid-state components and systems, logic devices, telemetry, radio astronomy, control systems analysis and antenna theory and knowledge. Under this program, antireciprocal Faraday rotation studies, as applied to the microwave region, were accelerated, resulting in evolution of the family of isolators, gyrators and circulators which are now in use. Two- and three-level masers, parametric amplifiers, transistors, reverse-bias semiconductor variable reactors, solions and solar power sources have emerged from the effort. Investigation of forward ionospheric, tropospheric, whistler-mode, meteor-burst scatter, extremely-low and very-low frequency, moon-bounce, satellite-bounce and other modes of propagation have been given much attention. Backward-wave, crossed-field, klystrons and other velocity-modulated types of tubes with application in a wide range of electronics systems have been developed.

Fast and high-flying vehicles produce environmental conditions which are much more severe than those encountered in the past. These conditions include temperatures up to 500°C, large shock, mechanical and acoustical vibrations, as well as nuclear radiation from fields as the Van Allen belts. Electron devices which will work satisfactorily under conditions encountered in space capsules are being examined and determined. These studies include analyses to determine structures and designs capable of tolerating these severe conditions.

Encouragement is given to studies in failure mechanisms which produce unsatisfactory performance in electronic devices, including failure-rate analysis, failure-prediction techniques, the effects of complexity, time-degradation, life factors, maintenance and redundance characteristics. New long-range electronics celestial and inertial navigation systems are products of this research. So are many new communications, radar and other systems whose design and successful operation depend on advances in the art of electronics which have come out of the broad research program and are available for solution of the problems of the space age.

This issue has been compiled to give a cross-sectional view of the Navy program in research in space electronics. Articles are presented on subjects ranging from communications to basic antenna research, and touching on radio and radar astronomy, control in navigation, satellite tracking and other topics. The authors have endeavored to make these contributions informative and stimulating. I am deeply grateful to them for their interest in the scientific program of the Navy. Acknowledgment is also due Dr. A. Shostak of ONR, who aided in preparing this material.

RAWSON BENNETT
Rear Admiral, USN
Chief of Naval Research

Spacious Fantasies*

JOHN PIERCE†

I'M AN old space fan. I believe wholeheartedly in the importance of space as a fresh field for scientific exploration. Our ideas concerning the solar system have already been jarred by satellite data. Furthermore, I believe in the importance of space for some military purposes and in its civilian potentialities in the field of broadband, transoceanic communication. But, I am shocked by most of what I hear and read concerning space.

Corny and long disproven fallacies of space travel appear and reappear in seemingly respectable newspapers and journals, and no one so much as lifts an eyebrow. Indeed, the way to fame appears to be the propagation of the big error, and a fantastic story suffers only from the competition of one still more fantastic.

Today, a great deal is known about our physical world which is as true in space as it is here on the surface of the earth where it was learned. Astronomers have known the laws which govern the motions of planets and satellites for many years. There have been many experimental verifications of the behavior predicted by special relativity. The laws of the propagation of radio waves are known. The power of chemical fuels is known. From newspaper reports of the failures and successes of missile and satellite shots we know a good deal about the present state of the technical art. What do these sources of real knowledge tell us about the present and future of the exploration and exploitation of space?

They tell us most emphatically that a great deal of what people say with a straight face is the sheerest fantasy. Take travel with velocities approaching that of light, for instance, which involves the much discussed "twin paradox."

Special relativity tells us that a clock whizzing past an observer will appear to him to run slower. Years ago, Ives verified that molecules moving at high speeds radiate lower frequency and redder light than they would if they were stationary; this shows that they vibrate more slowly when traveling fast. Mesons going with almost the speed of light last longer than slower mesons do; time passes more slowly for them, and they take longer to disintegrate. We can take it as an experimentally verified fact that clocks appear to run more slowly on swiftly moving objects.

One might think that this would lead to a paradox. *I* say that *you* are moving past me, and that *your* clock runs slow. *You* say that *I* am moving past *you*, and that *my* clock runs slow. However, in order to come back and compare clocks a space traveler must turn around, both with respect to the earth whence he departed, and with respect to the light and radio signals that are traveling toward him from earth. Because of this turning around, the space traveler's experience is just plain different from that of the stay-at-home on earth. One can utter many different sorts of words concerning this, but all that are consistent with relativity describe the same fact. Thus, when careful calculations are made concerning a journey out into space and back again, no paradox appears, and the unusual conclusion is as follows.

Suppose one twin stays on earth and another sets off at 99.5 per cent of the speed of light on a journey to the stars and back. Suppose the earth-twin ages ten years before the star-twin returns. When the star-twin gets back he has aged only one year though his brother has aged ten.

The first point to make is that relativity assures us that each twin has experienced the usual physical laws and a normal environment in every way. I once heard a rumor that a doctor wanted to study the effect of relativistic shrinking on organisms but I hate to believe that any scientist could be so poorly informed.

The second point to be made is that we can't expect in any foreseeable future to attain anything close to the velocity of light. We have all heard that a mass m is equivalent to an energy mc^2. When uranium 235 is fissioned, a thousandth of its mass is turned into energy. Imagine, now, that we could turn *every bit* of some sort of hypothetical space-ship fuel into energy (what an explosion!). The weight of fuel needed to attain 99.5 per cent of the speed of light would have to constitute 95 per cent of the initial weight of the space ship—and this just to get started. To stop would use up 95 per cent of our remaining 5 per cent. Counting also starting back and stopping again on earth, our space ship would have to be 99.999375 per cent fuel at the beginning of the trip, and we would have to turn this fuel into energy 1000 times as well as is possible in a fission bomb. In the first place, we can't do this and the prospects are dim. In the second place, would a passenger be likely to survive?

What is the truth about the relativistic *time dilatation,* or slow-running of fast-moving clocks? At satellite speeds we may in the near future hope to observe the effect by using an atomic clock which makes an error of perhaps one second in a thousand years. Moreover, with such a clock one could also observe an effect predicted by general relativity, but not yet clearly verified: that a clock

* Received by the PGMIL, October 29, 1959.
† Bell Telephone Labs., Inc., Murray Hill, N.J.

lifted up against the force of gravity would run faster. This same effect would cause a *red shift* in light from the sun or from other stars.

At attainable space speeds such time effects are barely detectable, not practically important. And the attaining of speeds at which such effects might become important belongs to the realm of fantasy, not of science and technology. Here I might observe that the newspapers recently expressed concern about micrometeorite impacts at near-light speeds. This is like Bluebeard worrying that he may not be able to endure the ennui of heaven.

If nothing else did, the nonsense written about relativity might make one suspect some other things which are said in connection with space. I suppose that one must mention antigravity. I know that respectable physicists are seriously concerned about gravity. They wonder, for instance, whether inertial and gravitational mass are exactly the same (no experiment has shown any difference), and they propose experiments at the very limit of observation. If a very brilliant young (or old) physicist of recognized competence wants to work on gravity he will, and if he needs money he should have it. To give money to less than the most brilliant for gravity research, and to expect results, makes me think of the man who took a running jump off a Chicago pier. He assured the rescuing policeman that he hadn't meant to commit suicide. Someone had bet him a million dollars to one that he couldn't jump across Lake Michigan, and, of course, he couldn't afford not to try.

Among the more modest fantasies, that which makes my blood boil and steam issue from my ears is the maneuverable manned space vehicle for military purposes. Modern aircraft travel so fast that an unaided pilot could scarcely detect, let alone shoot down, an enemy aircraft without the most sophisticated electronic aids. Speeds will be much greater in space. Maneuverability will be less, because one can't turn by pushing against the air (there isn't any). Fuel will be in short supply, so that it is only by using the most sophisticated guidance that one can get a payload to the desired point in space, and hopefully, in the not too distant future, to get it back again. All we need to louse things up completely is a skilled space pilot with his hands itching for the controls.

Of course, maneuverable space vehicles of a sort are in the building; these are anti-missile missiles, which are shot at other missiles and maneuvered toward them by means of radars and computers on the ground. The problem is very difficult but perhaps not insurmountable; the cost is great and may be prohibitive, but the stakes are tremendous.

What about nuclear energy for space flight? It has possibilities for interplanetary ships, if the nuclear vehicle is first boosted up out of the atmosphere by chemical rockets. In this case an atomic pile would be used to produce electricity and the electricity would be used to eject ions at high speed and so to push the vehicle gently forward over a long period of time. Solar power and solar sailing (propulsion by light pressure on huge metal foil or metallized plastic sails) are strong competitors for the interplanetary travel. All of this lies far in the future.

How far in the future do such things lie? One can't predict times when the technical problems are not even fully understood and are certainly not solved. Such prognostications are the source of the chronically slipping schedules which have been a prominent feature of our space programs. Another prominent feature is the cheerful acceptance of failure that could have been foreseen.

One might think that fantasies of space would be confined to loose talk about the indefinite and irrelevant future, but much nonsense involves serious matters. About these, fantastic statements are made, to which definite dates are attached. Thus, there have been confident talk and definite dates concerning nonexistent missiles of the future, while at the same time we hear of repeated if erratic and ill-understood failures of what should be the reliable missiles of today.

Perhaps what I have said so far may seem a little remote from space electronics, but I think that it has its lessons for that field as well as for any other new and growing branch of technology. Perhaps the sort of dangerous if amusing nonsense we have been exposed to concerning space can help us in overcoming similar nonsense in space electronics.

Surely, just as in space science and technology as a whole, it is important to take what is known into account. What is known embraces both fundamental scientific principles, such as those of relativity, and experimentally ascertained fact. Sometimes both of these have been disregarded.

Thus, I have heard tales that there is some sort of gain limitation on microwave antennas. I know gains of 60 db have been attained, and all one needs to utilize higher gains is an accurate and rigid structure. I have heard of limitations on system noise temperature, yet I know that noise temperatures below 20°K can be attained.

On the other hand, I have heard of very complicated transistorized code generators which will operate perfectly for years on end, of devices which will transmit good-quality speech using only 100 bits per second, and of devices which will recognize speech (not just a few words spoken in a few voices) and turn it into print. I know that all of these things are as mythical as the Phoenix, though, of course, they may come to be in some pleasant future.

It will pay the practitioner of space electronics really to ascertain the facts of science and technology before he plans a space electronics system. He should also ascertain the availability of particular components.

When does it make sense to talk of fairly definite dates for testing and manufacture of a system? Only when we can, at the outset, either buy satisfactory components with the required performance or at least go into the laboratory and see the satisfactory performance of a prototype of *every essential element in the system.* Heaven knows, it will be hard enough to get a tube or other device that

works well in the laboratory into even small-scale production by the time the system has to be going. Of course, in the case of a well-explored element such as a negative-grid tube or a klystron or traveling-wave tube one can count in advance on modest increases in performance or power—from 50 per cent to 100 per cent, perhaps, but if, for instance, the system calls for 5 or 10 times presently available power, dates make no sense whatever.

What does one do when a system calls for devices or performance which haven't been clearly demonstrated? It seems to me that one holds the system in abeyance and tries to bring the devices to a satisfactory state. The part that *is* within the art can be done in a hurry later. But, if one does build the rest of the system in the absence of critical components and then finds that the characteristics of the components aren't what he expected, he may have to make many costly changes.

We may contrast research and exploratory development with work toward very definitely stated ends. The purpose of research and exploratory development is to uncover new phenomena and to devise and bring to demonstrated operability new devices and new experimental systems. If either promises particular results, and especially if either promises particular results by *particular dates,* sense and honesty go out of the door and madness and deceit are invited into the house.

Development must develop things on the basis of what exists. Research and even exploratory development must admit with humility that they are seekers not seers, and that they cannot predict the details of the future or guide a development man through fields as yet untrod.

Of course the forgoing are rather general statements but I believe that they can be illustrated by particular instances.

For instance, for useful satellite communication systems and for planetary probes one needs electronic equipment, in some cases microwave tubes, with years of *assured* (not *average*) life. And the only kind of life we can be really sure of is *demonstrated* life. Even life on the ground cannot in the end be sufficient, but it is at least necessary.

Similarly, we need foolproof orientation equipment with an *assured* (not *average*) life of years. Again, this must be demonstrated first on the ground.

We can say the same concerning all the other components proposed for communication or reconnaisance systems. And, without adequate components, systems plans became dangerous nonsense.

Microwaves in the Space Age*

H. RICHARD JOHNSON†

Summary—**Consideration is given to the direction of future microwave device research and development based on requirements for space communication, tracking, search and surveillance, and interference and countermeasures. The crucial element in two-way communication with a space vehicle is the vehicle-borne transmitter. The large values of one-way transmission loss associated with interplanetary distances will require great improvements in these transmitters. Radar involves two-way transmission loss, so even more improvement will be required for tracking and search radars. Solution of interference problems will require increased instantaneous bandwidths. Accordingly, it is suggested that much additional microwave device research and development work is needed. Average power and efficiency of microwave tubes must be increased, with the longer centimeter wavelengths to be used for earth-based radars and 1-30 millimeter wavelengths to be used for radars to be borne in space vehicles. This work should concentrate mainly on traveling-wave tubes. Solid-state low-noise receiving devices and low-noise traveling-wave tubes must be extended to higher frequencies and broader bandwidths. Means of generating microwave power through the use of plasmas must be investigated. All types of microwave election devices must be adapted to the space environment.**

* Manuscript received by the PGMIL, October 29, 1959.
† Watkins-Johnson Company, Palo Alto, Calif.

Introduction

As MAN prepares to send machines from the earth, and ultimately to leave the earth himself, engineers and scientists who deal with radar and radio communication naturally tend to ask themselves what the peculiar needs of the coming space age will be in their field.

Certainly this area is crucial to the progress into space. First and foremost is the requirement of communication. Without communication from an unmanned space vehicle to the earth, that vehicle would be far less useful. Another important area is tracking. Radio tracking of space vehicles can give information even when the vehicle is optically invisible, and can always yield more accurate range information than optical means. In the future, the high specific impulse available from ion propulsion may make this an important area. Reasons of national security may make it important to have means for searching out space vehicles. Lastly, there is the area of interference and countermeasures, and the associated area of counter-countermeasures.

Communication

Consider first some of the requirements associated with space-age communication. The most obvious factor associated with communication with a space vehicle are the facts associated with the considerable cost per unit mass of launching. This means that the vehicle itself is often small, and its transmitter and power supplies must be small. While some satellites are relatively close to the earth and consequently the range of the communications link is relatively small, exceedingly large distances have already been attained and will soon become commonplace.

Two links are associated with two-way communication between the earth and a space vehicle, one transmitting from the earth to the vehicle and one from the vehicle to the earth. Since even the best receivers are not very massive compared to transmitters as a rule, it is obvious that the most important link is the one involving transmitter in the vehicle and receiver on the earth. Receivers will employ masers, parametric amplifiers, or low-noise traveling-wave tubes depending on frequency and bandwidth requirements.

Choice of the best frequency for communication between a space vehicle and the earth is a complex question. The transmissions must be capable of penetrating the ionosphere, a plasma surrounding the earth which has ion densities which sometimes exceed 10^6 electrons per cm^3, so this establishes a lower limit on the frequency which can be used which is on the rough order of 20 mc. The signals must also be capable of penetrating the atmosphere, a blanket a few miles thick containing oxygen and water vapor among other things. By virtue of its electric dipole moment, the molecule H_2O has many transitions capable of absorbing microwave radiation in the vicinity of 24,000 mc. At lower altitudes, broadening of these lines occurs associated with the rapid collisions of the water molecules against other air molecules, and the over-all one-way transmission loss through the entire atmosphere at normal incidence reaches a peak of the order of 2 db at 24,000 mc for an average humidity of 66 per cent. This figure is, of course, substantially higher for oblique incidence or under conditions of fog, etc. The atmosphere becomes somewhat more transparent again at a frequency of about 30,000 mc, but then rises rapidly to nearly total opacity (more than 100-db attenuation) at about 60,000 mc. There are also other "windows" in the general vicinity of 100,000 and 500,000 mc where the total one-way atmospheric absorption for normal incidence may again drop to the order of a few db. At frequencies much higher than this, a multitude of overlapping absorption bands associated with H_2O, CO_2, and O_2 are believed to reduce the transmission to unusable levels. These considerations appear to establish that there is also an upper limit on the frequency useful for satellite-earth communication on the order of 500,000 mc.

Within the four decades of frequency lying between 20 and 500,000 mc, choice of frequency may be based upon the facts that transmitters of good efficiency and low mass are more readily available at the lower frequencies, and antennas capable of radiating almost isotropically are also rather easy to achieve at the lower frequencies. Isotropic antennas eliminate the need for attitude stabilization of the vehicle.

On the other hand, use of the lowest frequencies severely prejudices the bandwidth of the channel which can be achieved and consequently the rate at which information can be telemetered over that channel. Early Russian satellites used the frequencies of 20 and 40 mc. Early United States satellites used 108 mc. Need for higher data rates than can be achieved at these frequencies will push frequencies to 2000 mc or even higher.

As the range over which the information must be sent rises beyond the lunar distance of 240,000 miles, the need for greater communication range will suggest the use of antennas producing sharp beams, even though this will require attitude stabilization of the vehicle. Since a typical antenna—a paraboloid, for example—will produce a beamwidth proportional to the quotient of wavelength divided by antenna diameter, it will be natural to seek higher frequencies. Another reason for this may be that in the 1000- to 10,000-mc region there is a tendency to get more output power per pound from higher-frequency tubes. Cold antennas may enable sharper beams than this.

This tendency to get more output power per pound as frequency increases can be very simply understood. One easy way to increase the frequency of operation of an electrostatically-focused microwave tube is to reduce all of its dimensions in the same proportion as it is desired to reduce the operating wavelength. The tube will then, of course, have a weight reduced in proportion to the cube of the wavelength-reduction factor. The limitations on this process are those of cooling, cathode current density, and arcing. When the dimensions are reduced by a factor, the temperature drop between heat source and sink must increase by the same factor. The process may be continued until high internal temperatures require the temperature of the heat sink to be lowered, a process involving more weight, or until gas evolution or melting of part of the tube limits the process. The cathode current density limitation occurs because as the tube is scaled to a smaller size, the area of the cathode is reduced by the square of the scale factor. This raises the cathode current density in proportion to the square of the wavelength-scaling factor. Eventually, the maximum density available from known cathodes is reached, and the process cannot be continued. The operating voltage of the tube can then be raised, but this also tends to raise the weight. The arcing limitation occurs because as the spacings between electrodes within the tube are decreased while the voltages between electrodes are maintained constant, the voltage

gradient increases. Finally, the point is reached at which a vacuum arc can develop between the electrodes, resulting in damage to the device.

Magnetically-focused tubes also tend to decrease in weight as frequency is increased. The weight of the tube exclusive of the magnet decreases for the reasons outlined in the last paragraph. The volume over which the magnetic field must be maintained decreases as the cube of the wavelength-scaling ratio, as described in the last paragraph. But, unfortunately, the value of the magnetic field which is required to constrain the electrons to pass through the reduced passages orthogonal to the direction of the magnetic field must be increased so as to maintain the ratio of electron gyrofrequency to operating frequency constant. That is, the strength of the magnetic field increases as the square of the wavelength-scaling ratio. The magnetostatic energy stored in the volume over which the magnetic field must be maintained is accordingly reduced, but only in inverse proportion to the wavelength-scaling ratio. The mass of permanent magnet required to establish this magnetic field is proportional to the magnetic stored energy, so is also reduced in inverse proportion to the wavelength-scaling factor.

What direction should advances in the microwave-transmitting-tube art take to complement this tendency to higher-frequency satellite-borne transmitters? A most promising direction appears to be the exploitation of the electrostatically-focused traveling-wave tube. Use of various electrostatic focusing schemes should enable the development of transmitting oscillator tubes of light weight and good efficiency at frequencies up to 10,000 mc. By the use of known techniques, it should be possible to develop these oscillators so that they can be electronically frequency modulated with a channel several megacycles wide.

Through the use of beryllia, a ceramic material now becoming commercially available for insulators within the tube, it should be possible to develop average power output from these electrostatically-focused tubes of the order of 1 kw at 6000 mc. Efficiencies of the order of 50-75 per cent should be attainable through the use of suitable depressed-collector techniques.

The electrostatically-focused traveling-wave tube is believed substantially superior to crossed-field or magnetron-type devices because of its lower weight. An often-cited advantage of crossed-field interaction is its high efficiency, but, as has just been noted, this efficiency can be equaled or bettered by the lighter traveling-wave tube for power levels less than 1 kw and frequencies below 10,000 mc.

Techniques for communication between a space vehicle in the cis-lunar region and the earth can probably be based on use of the electrostatically-focused traveling-wave tube. But as distances increase, there will be further drive toward higher frequencies for narrower beamwidths, and toward higher average power levels. Channel bandwidths will be reduced and integration times increased. Devices capable of generating 1000 to 100,000 watts of average power in the 10,000-mc region will be needed. These steps will have to offset the increase in inverse-square transmission loss associated with increasing the distance from 240,000 miles (moon) to 25,000,000 miles (closest approach of Venus), 48, 56, 380, and 2700 million miles (closest approaches of Mars, Mercury, Jupiter and Pluto respectively). The increased one-way transmission losses with respect to the moon are respectively 20, 23, 24, 32 and 40 db.

This requirement for 1000 to 100,000 watts of average power at 10,000 mc for communication in interplanetary space can best be satisfied by the use of a beam-type device, that is, a klystron or a traveling-wave tube. Crossed-field devices (magnetrons, amplitrons, etc.) will be hard-pressed to produce this amount of power at this frequency. They will be plagued with anode-melting problems and unreliability associated with the small anode necessary at this frequency. A basic limitation of crossed-field devices is that they require dissipation of the spent beam at a substantial fraction of its full power density on the miniature anode structure within the tube. Klystrons and traveling-wave tubes, on the other hand, are devices in which the powerful electron beam does not strike the RF interaction circuit within the tube. The beam in these devices passes through the RF interaction circuit region in which a considerable amount of its kinetic energy is converted to RF energy, but it need not strike that circuit. Instead of the spent beam being dissipated on the RF circuit, it is removed from the RF circuit and allowed to enter a much larger element of the tube, the collector, which can specifically be designed to decelerate, spread out, and absorb the spent beam at a much lower power density than can be done in a crossed-field device. The wavelength-scaling laws do not limit the size of a collector, but they do limit the size of an RF structure.

It will probably be desirable to obtain instantaneous bandwidth of the order of 100 mc or more in this interplanetary communication tube. In that case, the traveling-wave tube will prove superior to the klystron.

Communication using the tube described in the last few paragraphs will certainly be cumbersome at best at the longest ranges in the solar system. But means of generating substantially more power, for example 10,000 watts at 500,000 mc, are simply not available at the present time. Substantially more basic research is needed to satisfy this requirement. Such research should involve electron-beam techniques as well as ion-plasma work. Enough is known about electron-beam techniques so that it is apparent that considerable progress can be made in this direction, although there may be little chance of achieving the ultimate goal. Use of plasmas, on the other hand, is far less well understood at the present time. Over the next five or ten years it is unlikely that any practical plasma (or other) devices capable of generating huge amounts of average

power at millimeter wavelengths will be developed. On the other hand, since a break-through is needed, research should be far-ranging and unfettered. Work on traveling-wave tubes for super power should, however, be pursued actively in parallel, because here the prospects are more definite.

It is worth mentioning that it is probable that the use of CW or FM techniques for communication over the longest ranges may be replaced with the use of pulsed techniques. Ultimate theoretical communication range for a fixed amount of information is, of course, fundamentally dependent upon the product of average transmitted power and time of transmission. But it is easier to generate more average power at high peak power. This is so because of the basic fact that the higher-voltage structures associated with production of higher peak power can be larger, and because it is possible to obtain higher current densities from cathodes under pulsed operation than under CW operation.

It is thus no surprise that the highest-power tubes in the millimeter range have been pulsed magnetrons. But as outlined earlier, fundamental considerations indicate that development of beam-type tubes in this region of the spectrum would soon eliminate the crossed-field devices from the competition. This prediction can be circumstantially substantiated by noting that shortly after World War II, the highest power which had been generated in the 3000-mc region of the spectrum had been obtained from pulsed magnetrons. But the work at Stanford University in connection with the development of the microwave linear accelerator there has produced a klystron with an output of 50 megawatts peak, a figure far in excess of that which has been produced by crossed-field devices, and this is so despite the considerably greater technical maturity of the magnetron. Traveling-wave tubes, of course, are essentially identical with klystrons in ultimate power-producing ability.

Millimeter-wave signals transmitted from interplanetary space to the earth will, of course, have to contend with the absorption bands in the earth's atmosphere. In addition to the absorption already noted, the offending air molecules also radiate microwave noise at a level dependent upon their temperature. Near the surface of the earth, that temperature is of the order of 0° Centigrade, but in the ionosphere temperatures can be much higher. Accordingly, the best reception system will probably involve use of a very high artificial earth satellite or the moon for a receiving relay station. This relay station will have to have the most sensitive receivers it is possible to make, since the temperature of space is about 0° Kelvin.

At the present time, receiving techniques for millimeter wavelengths are very poorly developed. Basic research on suitable solid-state maser materials may lead to break-throughs here. But, in addition, development of low-noise traveling-wave tubes for the millimeter wavelengths should be initiated. This would result in a first phase in which lowest noise figures are produced by the traveling-wave tube, and then in a second phase in which the solid-state devices produce the lowest noise figures but the traveling-wave tube is still used as an amplifier between the solid-state device and the mixer stage. In this second phase, the large stable gain at wide bandwidth of the traveling-wave tube will enable adjustment of the solid-state device for optimum bandwidth and stability.

Tracking of Space Vehicles

From a microwave tube standpoint, tracking a space vehicle which contains a transponder or beacon is quite similar to the problem of communication just discussed. But if it is assumed that the vehicle does not contain a beacon, the problem immediately becomes tremendously more difficult. This is so since the transmission loss must be suffered over the path both ways. The radar equation, with signal-to-noise ratio varying inversely with the fourth power of range, applies. Power levels many orders of magnitude larger than those for communication are required. In addition, huge antenna arrays are indicated. But because of the high angular rates of low-flying space vehicles, these large arrays must be capable of being steered rapidly and accurately. This immediately suggests that multiple-unit steerable-array or MUSA antennas such as have been used for years for transoceanic telephone communication reception should be adapted for microwave use, both on receiving and transmitting. Separate high-power transmitters should be connected to each element of the antenna, and the antenna sloughed through adjustment of the phases of these individual radiators.

These requirements simply emphasize the needs already cited for high-power tubes, except that here the emphasis should probably be placed on the 10,000-mc band and on super-high power levels per tube envelope. Lower frequencies might be refracted unduly by the ionosphere of the earth. Again, crossed-field devices are out of the question and beam tubes are indicated. It will not really be necessary to choose between traveling-wave tubes and klystrons, however, for at extremely high power levels large-diameter hollow electron beams will be employed. This will produce direct cavity-to-cavity coupling through the beam hole. The only difference between a klystron and a traveling-wave tube is that the cavities in a klystron are coupled only through the electron beam, whereas in a traveling-wave tube additional RF coupling between adjacent cavities is deliberately introduced. This coupling will be unavoidable in a super-power klystron (say, 1,000,000 watts average power at 10,000 mc). Typically, klystrons have less bandwidth than is obtainable from traveling-wave tubes. This can prove to be a disadvantage in an environment in which there is RF interference (band-crowding or enemy countermeasures). The fact that the super-power klystron automatically becomes a traveling-wave tube can become a blessing in disguise if the result-

ant bandwidth is used to enable the tracking radar to change frequency instantaneously in the event of interference.

Traveling-wave tubes can also be used as electronic phase shifters. It should be easy to develop special tubes, either for use as intermediate amplifiers in transmitters or in low-noise RF preamplifier tubes for receivers which can instantaneously shift their phase in response to an electrical signal. This can be accomplished with essentially no change in RF gain. Such phase-shifting ability would simplify electronic steering of the MUSA arrays.

Search Radar

Searching is substantially more difficult than tracking. That is, it requires more average power. This is so since the transmitter power cannot simply be concentrated as a searchlight on the target, but must continually be swept about looking for the target. If the beam used is extremely narrow, as is required for long range, covering the entire hemisphere (or perhaps sphere) takes a very long time indeed. On the other hand, if the beam is extremely broad, range is bound to suffer. Spending a shorter time on target reduces range by reducing integration time. It would appear that the solution might again be a MUSA array, but this time using a somewhat lower frequency. Perhaps an average power of 10,000,000 watts per envelope at about 3000 mc would be a suitable goal for the next 5 to 10 years.

Again, this tube must be a traveling-wave tube rather than a crossed-field device. The reason for not choosing a lower frequency is that low-flying space vehicles might be surrounded by a plasma sheath which would have a very low scattering cross-section for lower frequencies.

Earth Surveillance—Passive or Active Radar

Earth surveillance is a much simpler problem than searching or tracking space vehicles. Cloud surveillance through use of satellite vehicles can undoubtedly be quite important in the immediate future for weather prediction. Passive and active forms of this mapping are possible. Perhaps infra-red passive radar will be adequate for this purpose. But if passive ground mapping is desired which will be operational under all kinds of weather conditions, it may be desirable to proceed to millimeter or even centimeter wavelengths, since fog attenuation drops rapidly as frequency is reduced.

Crossed-field devices, notably crossed-field amplifiers, have an important area of application in satellite-borne earth-surveillance radars. Despite the severe limitations on the ultimate average power which can be obtained from these devices, they have an important weight advantage over beam-type devices in the realm of high peak power but low average power. For example, it is possible to construct such a device at 10,000 mc which, including its permanent magnet, will weigh only about 10 pounds but will be capable of producing 250-kw peak power at an average power of 250 watts. A comparable klystron or traveling-wave tube, including its focusing means, would be certain to be larger and heavier.

Passive Radar and Radiometry

To return to the area of passive microwave radars for a moment, the minimum temperature difference detectable is proportional to its noise figure divided by the square root of its bandwidth. It appears highly likely that a millimeter-wave traveling-wave tube will prove to have a better figure of merit for this application than any other device now on the horizon. Of course, such a millimeter-wave passive radar would be somewhat weather-sensitive, although not as seriously so as an infra-red device would be. Use of the 4000 to 8000-mc band might be preferred for its absence of sensitivity to the weather, despite some reduction in performance because of the reduced bandwidth. A traveling-wave tube covering this entire octave at a noise figure of the order of 1 db maximum could be developed over the next five years, and a tube with a maximum noise figure of 3 db in a much shorter time.

Navigation

Another interesting use for this 4000 to 8000-mc traveling-wave would be for purposes of radio navigation. At the present time, passive navigation under conditions of radio blackout and optical overcast is dependent upon simultaneous sighting of the sun and the moon. These are simultaneously above the horizon only 25 per cent of the time. With use of a passive radar including a tube of noise figure of 5 db or better and a reasonable antenna size, three radio stars will be visible at all times, changing use of such a radio sextant from a sometime thing to a reliable fact.

Interference and Countermeasures

Perhaps it is now in order to say a few words about interference, deliberate countermeasures, and means for defeating these. The classical method for overriding interference, from whatever cause, is the use of higher average power. This means, of course, that a basic premium must be placed on high average power for communications or radar when these services must be free from interference. On the other hand, if the objective is to generate interference, again a premium must be placed upon average power in the jamming tubes. Interestingly enough, however, the judicious use of wide instantaneous bandwidths can give the communication or radar transmitter an advantage over the jamming transmitter. It is extremely important to have microwave tubes capable of as much instantaneous bandwidth as possible so as to have the capability to design systems which can take advantage of this advantage over the jammer. It is also important to

have jamming tubes available which can produce extremely high average noise power over wide bandwidths.

Wide instantaneous bandwidth at high average power necessitates traveling-wave tubes.

Effects of Space Environment

So far, the function of microwaves in the space age has been the main subject of discussion. It is also interesting to consider the environment associated with space and the effect which this environment may have on microwave devices.

The ionizing radiations present outside the earth's atmospheric shield may inactivate solid-state devices, and have a life-shortening effect on the cathodes of microwave tubes.

Emission of gas from microwave power tubes may cease to be as important as it is now. Inclusion of large pumping orifices connecting the interior of the tubes to the environment of outer space can serve to remove gas at a great rate. This may enable operation of tube elements at temperatures which would not be feasible for use in sealed-off tubes within the earth's atmosphere. Recent measurements have indicated that the pressure in the earth's atmosphere except in the auroral zones varies as follows:

pressure	altitude
10^{-4} mm Hg	70 mi
10^{-6}	80
10^{-8}	190
10^{-10}	400
10^{-12}	600

In the auroral zones the pressure is roughly ten times higher.

Reliability is an especially important consideration for space age microwave devices. Failures of unmanned devices are extremely expensive and time-consuming, and failures of manned devices will cost lives. During the initial design of tubes, it will be more important than ever to keep in mind that cathode loading must be minimized, and back bombardment of the cathode by electrons and ions eliminated wherever possible. During the development phase, extensive shock and vibration testing should be conducted so that the resulting design will be as rugged as possible.

During the development of tubes which will be used in connection with super-power MUSA arrays such as discussed earlier, careful attention must be given to use of manufacturing techniques which will lead to minimum cost. But it is important to note that the cost per kilowatt of average power is not the important quantity to maximize, nor is the cost per kilowatt of peak power. Rather, the important quantity is the cost per average unit of RF energy, the number of dollars per joule. This may indicate use of lower peak and average powers per envelope and more tubes in a MUSA system designed for a certain average power. The life of each of the low-power tubes might be increased so much that the decreased power per tube is more than compensated.

Operation of high-frequency devices at extremely low temperatures can reduce their RF losses drastically because of incipient or actual superconductivity. Small super-directive antenna arrays and extremely efficient low-power microwave generators may become feasible.

Conclusion

From the discussion it is apparent that many of the requirements for communication, vehicle tracking and searching, surveillance, and navigation can only be met or can best be met through the use of microwaves. In order to meet these needs adequately, much research and development is needed in the following areas: 1) increasing the power and efficiency of beam-type microwave tubes, 2) extension of solid-state low-noise receiving devices and low-noise traveling-wave tubes to higher frequencies and broader bandwidths, 3) investigations of means of generating microwave power through the use of plasmas, and 4) adaptation of all types of microwave electron devices to the space environment.

The Role of Radar in Space Research*

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Introduction

WHEN we think about the exploration of space we visualize a rocket ship blasting off for a trip around the solar system. Let us not forget, though, that astronomers have been exploring space for hundreds of years. Lately, radio astronomy has made significant contributions to the understanding of the universe. Similarly, radar has assumed an increasingly important place in space research. Finally, rockets and satellites permit direct contact with outer space.

These various methods complement each other and provide independent descriptions of the solar system. Compared with either astronomical or rocket explorations, radar is unique in that it obtains its information by measuring the effect of matter in space on a known transmitted signal. This allows accurate distance determinations to various solar bodies and provides an independent method to describe features and composition of some extraterrestrial surfaces.

Radar Astronomy Problems

Radar investigations are necessarily confined to the solar system. In this region radar can investigate the densities, distances, and dynamic properties of ionospheric clouds and solid bodies. The results of these investigations may also provide greater insight into phenomena occurring outside the solar system. Some of the accomplishments in this field and several proposed projects will be discussed in this article.

Ionosphere

The exploration of space by pulsed radio signals began in 1925 when the Carnegie Institution of Washington [1] and the Naval Research Laboratory jointly obtained echoes from the ionosphere—the upper layers of the earth's atmosphere which are continually ionized by solar radiation. The results of such measurements are very important to space research, because the atmospheres of the sun and of some of the planets and probably the spaces between these bodies contain ionized gases. To obtain pertinent information through radar reflections from ionized gases, one must understand the complex reflection and scattering mechanisms. When the return signal is carefully analyzed, deductions can be made concerning the density and kinetic temperature of the reflection medium, as well as the group motions of the electrons and magnitude and direction of any magnetic field present.

Many other studies of the ionosphere are being conducted by radar. Echoes received from man-made satellites, auroras, lightning, and from several unidentified sources have helped to explore the behavior of the ionosphere. Electron densities and electron motions at different heights, and measurements of the earth's magnetic field have been obtained from an analysis of these echoes. There has been considerable success in relating these observations with weather, communications, solar activity, and even with cosmic rays. In the future, information may be gained concerning electron temperatures, Stoermer ring currents and, possibly, Van Allen belts at distances of several earth radii.

Ion Clouds

In 1947, J. S. Hey and G. S. Stewart, [2] of the British Ministry of Supply, detected echoes from meteor trails —columns of intense ionization left in the wake of meteors. Initially, these columns are long and thin, but with the passage of time they spread to form patches or clouds. The velocity of the meteors, and the drift, height, shape, persistence, intensity, and number of meteor trials can be deduced from radar echoes. Also, ionic clouds produced by atomic blasts, hot rocket exhausts, and high-velocity rockets in the ionosphere have been detected at the Naval Research Laboratory. As an important consequence of these studies, it has been shown that such ion clouds can support a communications or monitoring system between widely separated points on the earth's surface.

Moon

Radar astronomy was first brought to the attention of the world when the Army Signal Corps contacted the moon in 1946. [3] The first lunar radars used long pulses, low frequencies, and narrow band-pass receivers. Owing to the limitations of the equipment, it was not possible to tell whether the echoes were coming from the entire exposed surface of the moon or from a smaller area. More recently, J. H. Trexler [4] of the Naval Research Laboratory discovered that most of the radar return seems to come from the central area on the moon, less than 300 miles across. This was an important discovery. If the moon reflected like a rough surface, as was previously supposed, the impinging radar pulse would be unevenly reflected—some portions of the pulse coming from the relatively closer central region of the lunar sphere, and other portions coming from the more distant edges of the moon. The moon would be unsuitable as a communications reflector. The actual echo pulse is a discrete, recognizable signal. Using this property, Trexler sent voice and music signals to the moon and back. Subsequently, the authors of this article made precise measurements of the distance to the moon at a wavelength of 10 centimeters. [5] Accurate measurements of the distance to the moon from various points on the earth improve our knowledge of the size

* Received by the PGMIL, October 29, 1959.
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and shape of the earth. Of course, this information would also be valuable for navigational purposes. Measuring radar range to the moon for an extended period should result in an independent determination of the lunar orbit. From this, a new determination of the moon-earth mass ratio is possible.

In 1954, W. A. S. Murray and J. K. Hargreaves [6] of the University of Manchester related the slow fading of the moon echo with Faraday rotation changes. (Faraday rotation is the shift in polarization of an electromagnetic wave as it traverses the ionosphere in the presence of the earth's magnetic field.) By measuring the total Faraday rotation, J. V. Evans [7] found that the total electron content in the earth-moon path was twice the amount expected from standard ionospheric measurements.

Another way of obtaining this information would be to use two synchronized pulse radars, one at about 100 mc and the other near 3000 mc, and to measure the frequency dependence of the propagation time between the earth and the moon. From this, the total number of electrons along the beam path could be calculated.

A radar system specifically designed for evaluating the surface characteristics of an extraterrestrial object would be worthwhile. Lunar echoes from radars employing variable pulse widths and narrow antenna beamwidths can yield considerable information about the surface of the moon. For example, they can show the variation in height between mountains and plains near the center of the lunar disk. Large spikes, which appear in the initial portion of the echoes obtained from the radar used by the authors, have been attributed to flat areas on the surface. The fast "fall-off" of these spikes led the authors to speculate that the average roughness of the moon's surface may be comparable to that of sandy soil. This estimate lends credence to the suggestion that the moon may be covered by a layer of dust. Refined echo analysis could give electrical characteristics of the reflecting surface from which one could estimate the surface composition.

Venus

A recent breakthrough in radar astronomy occurred when contact was made with the planet Venus, which approaches the earth more closely than any other planet in the solar system. Scientists at the Lincoln Laboratory of M.I.T. accomplished this feat in 1957, during a near approach of Venus to Earth. [8] However, the return signals were so obscured by noise that it took a year of effort, using the most advanced analysis techniques and high-speed computers, to uncover the echo. Recently, Venus was again in inferior conjunction with the earth, and many of the world's largest radars, including the 250-foot radio telescope at Jodrell Bank, England, were focused upon it.

Radar measurements of the distance to Venus will provide a better determination of many astronomical distances. The astronomical unit is the fundamental unit on which the scale of the solar system is based, and is defined as the mean distance from the earth to the sun. Relative distances of the planets from the sun and from each other are known quite accurately in terms of the astronomical unit, but the absolute distances are known only to about 0.1 per cent. Therefore, an accurate measurement of the distance to Venus could improve our knowledge of astronomical distances. The surface of Venus is always obscured by clouds of dust or vapor. The amplitude, pulse shape and fluctuation of radar echoes from Venus could be analyzed to inform us of some of the properties of the surface. In addition, the planet's rotation period could be estimated from the Doppler frequency spread of the echoes.

Asteroids

The present determination of the astronomical unit depends largely upon trigonometric measurements of the distance to the asteroid Eros; its orbit is well known, and it occasionally passes quite near the Earth. Other asteroids also approach the Earth; for example, in 1937, Hermes passed at a little more than twice the moon's distance. Although most of these asteroids are small—probably less than five miles in diameter—it is likely that they have a high radar reflectivity. This leads to the interesting possibility of obtaining radar echoes from asteroids. If the orbit of an asteroid is sufficiently well known, radar contact could aid in checking the astronomical unit. If the orbit is not accurately known, such contact might help determine the orbit.

Sun

Let us now turn to the largest radar target in the solar system—the sun. The sun subtends about the same solid angle from the earth as does the moon, and therefore would intercept an equivalent amount of radar signal. However, the longer return path would result in a greater signal loss. Moreover, the sun generates a large amount of radiation, which would tend to mask radar echoes. The amount of attenuation of the signal in the sun's corona, and the corona's back-scattering directivity are little-known factors. These considerations imply that to obtain usable reflections from the sun we need a very large antenna, a powerful transmitter, and a band-pass determined by the assumed rotational velocity. A relatively low frequency is required to reduce absorption in the corona. [9] If we can obtain solar echoes at several different frequencies, we will have a powerful tool for investigating the vertical distribution of electrons in the sun's atmosphere. Another fascinating possibility is the detection of the streams of charged particles known to be flowing from the sun toward the Earth. We would like to know the velocity of these streams and how they disperse during their trip.

Technical Progress

The techniques of radar astronomy are still in their infancy; yet considerable progress has already been made. A little more than 12 years ago, the Army Signal Corps [3] and, coincidentally, a Hungarian, Z. Bay, [10] obtained

echoes from the moon. Both investigators used relatively small antennas and low-power transmitters. The Army Signal Corps overcame this handicap by employing a very narrow band-pass receiver to obtain a good signal-to-noise ratio; however, this limited band-pass prevented the determination of the fine characteristics of the echoes. Z. Bay designed a novel signal-detection system, an ingenious mechanical-chemical integrator utilizing a rotating switch to obtain range-time increments and an electrolysis process to indicate the relative signal power in these range elements. Present moon radars do not require such specialized signal-detection methods because of overall improvement in the radar art. Yet when we start looking for echoes from the sun and the planets, the signals will be small compared with the noise, so we must resort to information-processing techniques.

Receivers

The signal-to-noise ratio for radars that will be used to probe the planetary bodies can be improved by reducing the receiver noise. The optimum in noise reduction will probably be obtained through the use of special solid-state amplifiers such as the ruby MASER (Microwave Amplification by Stimulated Emission of Radiation). One such MASER amplifier, built by C. H. Townes, J. A. Giordmaine, and L. E. Alsop of Columbia University [11], and installed in the 50-foot radio telescope at the Naval Research Laboratory, has been used by the astronomers to measure radiation from some of the planets and from several radio stars. Using this device, the receiver sensitivity of a theoretically perfect receiver—even if that receiver were situated in outer space—would still be limited by noise from the galactic background. Electronic computers can be applied to separate signals from background noise. Present autocorrelation techniques are capable of detecting signals in the presence of random noise even though the power in the signals is less than the noise power by a factor of 100 or more. We have already noted that this technique was effectively used in the M.I.T. Venus experiment.

Transmitters

The art of manufacturing high-power transmitters is steadily advancing; 30-megawatt klystron amplifiers are already being produced, and one can talk about radar transmitters having peak powers of 100 megawatts or higher.

Antennas

The most severe equipment requirement of a space-research radar will be that of obtaining a very large steerable precision antenna. This is necessary to obtain a beam pattern comparable in size with the subtended angle of the planetary target. The 250-foot parabolic antenna in operation at Jodrell Bank, England, is the largest antenna at present. Yet, this radio telescope cannot be used effectively at the higher radar frequencies. The design of a large steerable microwave antenna will require the solution of some rather difficult engineering problems.

Fig. 1—NRL's 50-foot radio telescope, with MASER amplifier mounted on tripod.

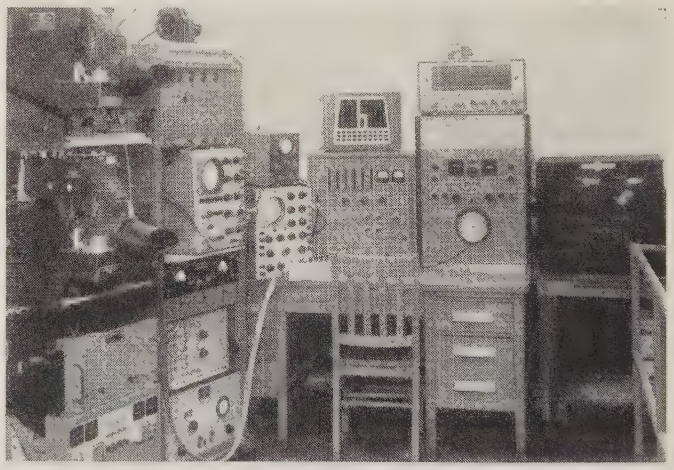

Fig. 2—The authors' moon-radar timing, monitoring, and recording equipment.

Space research by means of radar offers definite advantages, since a controlled signal of known characteristics is used as a probe, and distance can be measured accurately. Radar investigations of the ionosphere have proven exceptionally valuable to weather and to communications research. Echoes from the moon and from artificial satellites have pointed out the possibility of using them for communications and as reference points for mapping the earth. Radar investigations of the sun and the planets are promising fields for future work. Extremely large antennas, powerful transmitters and special receivers will be needed. Although the cost of this equipment will be high, it will seem small when compared with the value of the information it will make available.

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A Radio-Astronomy Project at the University of Illinois*

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The Illinois Radio-Telescope

Among the radio-astronomy projects that are supported by the Office of Naval Research is the large radio-telescope of the University of Illinois. This is a parabolic cylinder reflector whose dimensions are 600 feet north-south and 400 feet east-west. Its focal length is 155 feet. The surface is to be of graded earth covered with prefabricated asphalt liner for erosion control. Over this will be placed a wire mesh to act as the reflecting surface. The feed elements along the focal line will be carried on the underside of a catwalk supported by four wooden towers 165 feet high. The catwalk is 425 feet long and will carry some 300 feed elements. The focal line lies in the meridian plane, and the beam can be swung in this plane by electrical phasing of the feed elements. The beamwidth between halfpower points is approximately 20 minutes of arc, and the operating frequency will be about 600 mc.

The construction in this fashion of so large a reflecting surface—about 5.5 acres—presents both excavation and drainage problems. These have been partially solved by making use of a natural topographic feature. Some 35 miles east of Champaign-Urbana, where the University of Illinois is situated, there was found a well-drained, steep-sided ravine, running north-south and having approximately the dimensions of the reflecting surface. Thus, nature has already performed the main part of the excavation; what remains to be done is to grade and shape the sides and bottom of the ravine to the exact surface of the parabolic cylinder. The location of the radio-telescope lies some five miles south-east of Danville, Ill., in a region which tests have shown to be fairly free of local man-made radio noise.

The radio-telescope will, of course, be a transit instrument, the rotation of the earth for each setting of the beam bringing successively into view the radio sources lying in a band 20 minutes wide in declination. It is hoped to devise a method of electrical phasing that will permit the examination of a band of total width in declination of 60°—some 30° on each side of the zenith of the point of location whose latitude is approximately 40° N. Since the side-lobes of the instrument will be relatively weak, accurate positions, flux-densities and information about the spectra of galactic and extragalactic radio-sources should be obtainable. It is hoped eventually to record the data directly on punched tape or magnetic tape and to analyze them on the Illiac, the University's high-speed digital computer.

A Distance Problem in Cosmology.

The anticipated relative freedom of this radio-telescope from side-lobe and other ambiguities, its narrow beam, and its high sensitivity [10^{-26}w m^{-2}(c/s)$^{-1}$ should be attainable] render it particularly suitable for the study of faint radio sources outside the Galaxy. The first task, therefore, will be to produce a catalogue of extragalactic radio sources, giving their positions as accurately as possible and their flux-densities at the operating frequency. There are at present two such catalogues in existence, one produced by Mills and his co-workers in Sydney, Australia, with the Mills Cross working at 3.5 meters;[1] the other, by Ryle and his colleagues in Cambridge, England, using an interferom-

* Manuscript received by the PGMIL, October 29, 1959.
† University of Illinois Observatory, Urbana, Ill.

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eter working at 3.7 meters.[2] The regions covered by these surveys overlap, and it is a disturbing feature of the investigations that there is little agreement as to the position of sources in the overlap area. The difficulties in locating the position of a source inherent in the Sydney and Cambridge instruments make it likely that both catalogues have serious defects, and in any case the lower limits of flux-density are relatively high—7×10^{-26}w m^{-2}(c/s)$^{-1}$ for the Australian and about the same for the Cambridge instruments.

It is usual, in such surveys, to give the cumulative totals of sources, N, to successive limits of flux-density S. In the Australian survey, for example, the limits range from 160×10^{-26}w m^{-2}(c/s)$^{-1}$ to 7×10^{-26}w m^{-2} (c/s)$^{-1}$. One question of interest connected with such surveys concerns the distances which correspond to the limits of flux-density, and it is this point which will be discussed below.

The extragalactic radio sources are called Class II sources by the Australian investigators, and a small percentage of these sources has been identified with optical objects. When this identification has proved possible, the objects have turned out to be galaxies, often presenting special peculiarities. Perhaps the galaxy contains some unusual internal feature such as the jet of gas in NGC 4486; or there is a confused structure that has been interpreted as a collision between two galaxies as in NGC 1275 and Cygnus A; or the galaxy contains two or more bright centers instead of the customary single one. It seems difficult to avoid the conclusion that Class II radio sources are indeed galaxies and that the obstacle preventing optical identifications is not merely uncertainty in the catalogued positions; one may suspect that these sources are also very remote and therefore inconspicuous objects even on the Mount Palomar Sky Atlas.

But if Class II sources are galaxies, their radiation in the radio domain must presumably share in the red-shift phenomenon characteristic of their optical emissions. The increase in wavelength $d\lambda$ in a spectral line of wavelength λ is such that the ratio

$$\delta = \frac{d\lambda}{\lambda}$$

is constant for all lines in the spectrum of a given galaxy. This was experimentally verified, for example, by O. C. Wilson[3] for the galaxy NGC 4151. He measured $d\lambda$ for 12 lines in the range 3.4 to 6.6×10^{-5} cm and found that the ratio δ was indeed constant within the errors of measurement. The only satisfactory interpretation of such spectral line displacements that has been proposed so far is that they arise through the Doppler shift produced by a velocity of recession. The classical Doppler velocity $c\delta$ of NGC 4151 is 967 km/sec and, had a displacement of this amount been observed in an object in our own galaxy, for example in the expanding shell of a nova, no astronomer would have hesitated to accept the velocity interpretation. But, for the galaxies, the spectral line displacements can be so large—up to the equivalent of classical Doppler velocities of 60,000 ($\delta=0.2$) or even 120,000 ($\delta=0.4$) km/sec—that questions are sometimes raised as to the validity of the velocity interpretation. Various attempts have been made to argue that the spectral-line displacement is produced by some physical action on light in the intervening space between source and observer.[4] But no plausible mechanism has been suggested for this action which must operate on all optical frequencies from the ultra-violet to the red in just the right way to mimic a Doppler displacement.

If the red-shift in the optical range is only satisfactorily interpretable as the result of a velocity of recession, it would be miraculous if the radio waves emitted by galaxies were immune from this effect. Nevertheless experimental confirmation is desirable, and it is therefore unfortunate that the red-shift which Lilley and McClain believed they have observed in the 21-cm radiation from Cygnus A has not been confirmed. A repetition of the experiment by Jennison at Jodrell Bank and another repetition by Lilley and McClain have apparently given null results.[5]

That the red-shift increases with the distance of a galaxy is undoubtedly true. But both theory and observation now show that Hubble's original assumption of a linear increase with distance is no longer tenable. The red-shift is indeed proportional to distance so long as both are small on the scale of cosmic distances, for example, up to red-shifts of amount 0.05 or 0.06. Thereafter distance becomes a more complicated function of the red-shift, a function which is not unique but depends on the choice of the uniform model of the universe.

Assuming, then, that Class II radio sources are galaxies and that they share in the red-shift phenomenon, we ask if it is possible to obtain an estimate of the distances to which the limits of flux-density in the Australian, or indeed any other, survey correspond. One way of doing this is to make the very crude assumption that all the sources covered by a survey are of the same intrinsic power output, that each of them is intrinsically identical with what will be called the "unique source." Then each limit of flux-density in the survey corresponds to the flux-density which the unique source would shed on the earth when it is placed at successively greater distances. Placing it at different distances, how-

[2] J. R. Shakeshaft, M. Ryle, J. E. Baldwin, B. Elsmore and J. H. Thompson, "A Survey of radio sources between declinations −38° and +83°," *Mem. Roy. Astron. Soc.*, vol. 47, pp. 106–154; 1955.

[3] O. C. Wilson, "Proportionality of nebular red shifts to wave length," *Publs. Astron. Soc. Pacific*, vol. 61, pp. 132–133; June, 1949.

[4] See, for example, the photon-photon interaction proposed by E. Findlay-Freundlich, in "Red shifts in the spectra of celestial bodies," *Proc. Phys. Soc.* (*London*) *A*, vol. 67, pp. 192–193; February, 1954; "Red shifts in the Spectra of Celestial Bodies," *Phil. Mag.*, vol. 45, ser. 7, pp. 303–319; February, 1954. Also, criticisms by W. H. McCrea, in "Astrophysical considerations regarding Freundlich's red-shift," *Phil. Mag.*, vol. 45, ser. 7, pp. 1010–1018; October, 1954.

[5] Private Communications; July and October, 1959.

ever, also means that its radiation would be affected by red-shifts of different magnitudes. Admittedly we have at present no really satisfactory method of assigning to the unique source its intrinsic power output, because the intrinsic power outputs of a sufficient number of Class II sources have not yet been determined for lack of knowledge of their distances. Nevertheless, it is possible to obtain some light on the distance problem by asserting that the unique source, if placed at the distance of some observed source, would have the same flux-density at the earth and the same red-shift as does this observed source. The observed source in question will be called the standard source and quantitities referring to it will be denoted by the suffix s. By trial and error, the author has found that results of interest can be obtained if two standard sources are selected in turn, namely, the moderately strong source NGC 1275 and the very strong source Cygnus A. We make the assumption, of course, that the radio source has been correctly identified with the pair of colliding galaxies in the case of Cygnus A. For the instrument and frequency used in the Australian survey, the observed flux-densities, S_s, and optical red-shifts, δ_s, of the two standard sources are:

NGC 1275: 240×10^{-26}w $\text{m}^{-2}(\text{c/s})^{-1}$, $\delta_s = 0.018$;
Cygnus A: $19{,}000 \times 10^{-26}$w $\text{m}^{-2}(\text{c/s})^{-1}$, $\delta_s = 0.056$.

The distances of these standard sources, calculated from their red-shifts, are uncertain, ranging from 1.18×10^8 to 2.36×10^8 light-years for NGC 1275 and from 3.6×10^8 to 7.3×10^8 light-years for Cygnus A. But the red-shifts are observational data that can replace the distances of the standard sources and the red-shifts are known with considerable accuracy. Hence, we shall express all distances as multiples of the distance of one or other of the two standard sources without converting these to light-years or parsecs.

However, in order to find distances, the selection of a standard source is not sufficient; we must also know how the sources are moving and how this motion varies with distance whatever the magnitude of the distance may be. At the present time this information cannot be found from observation, but it may be obtained by selection of one or other of the uniform models of the universe based on the theory of general relativity or on the steady-state theory. The underlying principles on which these models are constructed show that many different motions with zero, positive or negative accelerations are consistent with a red-shift phenomenon and with the postulate of a uniform distribution in space of the galaxies. The important function in a model universe is the scale factor $R(t)$ which increases with the time alone. It has the property that any small volume, which has the value dv at the instant when $R=1$, has the value R^3dv when R is no longer unity. In addition to $R(t)$, a model universe is characterized by the space-curvature constant k, which may have one or other of the values $+1, 0, -1$. If $k=+1$, space is spherical and of finite volume; if $k=0$, it is Euclidean; and if $k=-1$, it is hyperbolic. Both the Euclidean and the hyperbolic spaces are of infinite extent. Uniform model universes differ from one another by having different functions, $R(t)$, in combination with different k. We shall choose three models in which the mathematical functions are as simple as possible. They are:

1) *Milne's model.* Here

$$R = ct, \qquad k = -1$$

so that every infinitesimal volume dv increases proportionately to the cube of the time, and space is infinite and hyperbolic.

2) *Einstein-de Sitter model.* Here

$$R = R_0(t/t_0)^{2/3}, \qquad k = 0$$

where R_0, t_0 are constants. Infinitesimal volumes increase as the square of the time; space is Euclidean and infinite.

3) *de Sitter universe (general relativity) and steady-state theory model.* Here

$$R = R_0 e^{(t-t_0)/t_0}, \qquad k = 0,$$

and the model is similar to case 2) except that volumes increase exponentially with the time.

Before proceeding with distance determinations using these uniform model universes, it is convenient to remember what would happen if the static Euclidean universe of classical physics were used to interpret the data. The Euclidean distance of a standard source being l_s, its flux-density when removed to a distance l would be S, where

$$\frac{S}{S_s} = \frac{l_s^2}{l^2} \tag{1}$$

and therefore, of course,

$$\frac{l}{l_s} = \left(\frac{S_s}{S}\right)^{1/2}. \tag{2}$$

Knowing S_s, the ratio l/l_s can be calculated for each limit S of the survey, as has been done in Table II below.

Returning to the uniform model universes in which the Class II radio sources share, by hypothesis, in the general motion of expansion, it can be proved that the analog of l is the luminosity-distance D.[6] Moreover, the emission of energy at radio frequencies varies as (frequency)^x in each frequency interval. Here, x, the spectral index, is a constant with a value lying between -0.6 and -1.2. It is then also possible to prove that the standard source, removed to luminosity-distance D for which the red-shift would be δ, would have a flux density S, where

$$\frac{S}{S_s} = \left(\frac{1+\delta}{1+\delta_s}\right)^{1+x} \frac{D_s^2}{D^2}, \tag{3}$$

[6] G. C. McVittie, "General relativity and cosmology," Chapman and Hall, Ltd., London, Eng., Sec. 8.5; 1956.

a result valid in any uniform model universe.[7] Thus, combining (2) and (3), we have

$$\frac{D}{D_s} = \left(\frac{1+\delta}{1+\delta_s}\right)^{(1+x)/2} \frac{l}{l_s}. \tag{4}$$

From this it follows that, if $x=-1$, the luminosity-distance ratio D/D_s is equal to the Euclidean ratio l/l_s. If x is not equal to -1, but lies in the range -0.6 to -1.2, the ratio D/D_s will depart significantly from l/l_s only if the red-shifts corresponding to S are large compared with δ_s. This is a very satisfactory result, for which the (frequency)^x law must be thanked. It shows that distances calculated from flux-densities by the static Euclidean universe hypothesis are likely to be fairly accurate whatever the motion of expansion of the universe may be.

To examine the matter a little further, (3) must be converted to one between S/S_s and δ. This can only be done exactly when the uniform model universe is completely specified, as is the case for all three of our models. The relevant formulas have been worked out and are:

1) *Milne*—

$$\frac{S}{S_s} = \frac{\delta_s^2(1+\frac{1}{2}\delta_s)^2}{(1+\delta_s)^{1+x}} \frac{(1+\delta)^{1+x}}{\delta^2(1+\frac{1}{2}\delta)^2}; \tag{5}$$

2) *Einstein-de Sitter*—

$$\frac{S}{S_s} = \frac{\{(1+\delta_s)^{1/2}-1\}^2}{(1+\delta_s)^x} \frac{(1+\delta)^x}{\{(1+\delta)^{1/2}-1\}^2}; \tag{6}$$

3) *de Sitter and steady-state*—

$$\frac{S}{S_s} = \frac{\delta_s^2(1+\delta_s)^{1-x}}{\delta^2(1+\delta)^{1-x}}. \tag{7}$$

These formulas illustrate how different assumptions regarding the nature of the over-all motion of expansion of the universe can change the relation between S/S_s and the red-shift. This is true even between cases 2) and 3) in which the curvature of space is the same (both Euclidean). Table I gives the results of the computations for $x=-0.75$. In the first column are found the successive limits of flux-density of the Australian survey. In the next three columns are the corresponding red-shifts calculated from (5), (6) and (7), assuming that all the sources in the survey are similar to NGC 1275. Columns five through seven contain the red-shifts under the hypothesis that all the sources are similar to Cygnus A. No alarm need be felt at the appearance of red-shifts greater than unity; it is only in classical theory that a red-shift equal to unity corresponds to a velocity of c. The uniform models of the universe incorporate a relativistic Doppler theory, and, as the case of special relativity shows, a red-shift of unity implies a velocity smaller than c.[8]

TABLE I

LIMITING FLUX-DENSITIES AND RED-SHIFTS

$S\times10^{26}$	NGC 1275 as standard			Cygnus A as standard		
	Model (1)	Model (2)	Model (3)	Model (1)	Model (2)	Model (3)
7	0.102	0.105	0.100	1.79	2.64	1.42
10	0.086	0.087	0.084	1.573	2.22	1.257
20	0.062	0.062	0.060	1.210	1.56	0.990
40	0.044	0.044	0.043	0.925	1.14	0.771
80	0.031	0.031	0.031	0.699	0.815	0.600
160	0.022	0.022	0.022	0.521	0.584	0.460

There are several interesting features of Table I. If NGC 1275 is typical of Class II radio sources, the effect of using different uniform model universes is small. From the red-shifts it can be concluded that the sources in the survey lie at distances that fall between that of the Coma cluster of galaxies ($\delta=0.022$) and a distance somewhat less than that of the Boötes cluster ($\delta=0.131$). If this is so, the difficulty in optical identification of the Class II sources must be due mainly to the ambiguities in their positions, because galaxies in this range of red-shift are easily recorded on the Mount Palomar Sky Atlas. However, the situation is quite different if Cygnus A is typical of Class II radio sources. A change of model now makes considerable alteration in the red-shift. More important still, even the inner limit of flux density, 160×10^{-26} w m^{-2}(c/s)$^{-1}$, now corresponds to a distance so large that galaxies at this distance are barely recorded on the Sky Atlas. Thus, lack of optical identifications is to be expected even if the positions of Class II radio sources are accurately given. Lastly, of course, we can conclude that if Class II radio sources have a scatter in intrinsic power output, and if the most frequently occurring source is intermediate in power between NGC 1275 and Cygnus A, the entries of Table I will give lower and upper bounds for the red-shifts corresponding to each limit of flux-density.

When $x=-(0.75)$, then (4) becomes

$$\frac{D}{D_s} = \left(\frac{1+\delta}{1+\delta_s}\right)^{1/8} \frac{l}{l_s}; \tag{8}$$

and thus, if NGC 1275 is the standard source, the maximum value of the factor

$$\left(\frac{1+\delta}{1+\delta_s}\right)^{1/8}$$

is 1.015. Hence, D/D_s is at most 1 or 2 per cent larger than l/l_s. The values of l/l_s for this case are shown in the second column of Table II; they are calculated from (2) and the entries in the first column of the table. The third column contains l/l_s similarly calculated for Cygnus A as standard source. The remaining columns

[7] G. C. McVittie, "Counts of Extragalactic radio sources and uniform model Universes," *Aust. J. Phys.*, vol. 10, pp. 331–350; 1957. Eqs. (3.05) and (3.06) with C and $p(=-1-x)$ treated as constants.

[8] G. C. McVittie, "Distance and time in cosmology: the observational data," *Handbuch der Physik*, vol. 53, pp. 445–488; 1959.

TABLE II

LIMITING FLUX-DENSITIES AND DISTANCE-RATIOS

$S \times 10^{26}$	NGC 1275 as Standard	Cygnus A as Standard			
			D/D_s		
	$l/l_s \simeq D/D_s$	l/l_s	Model (1)	Model (2)	Model (3)
7	5.86	52.1	58.8	60.8	57.8
10	4.90	43.6	48.4	50.1	47.9
20	3.46	30.8	33.8	34.4	33.4
40	2.45	21.8	23.5	23.8	23.3
80	1.73	15.4	16.3	16.5	16.2
160	1.22	10.9	11.4	11.5	11.4

contain D/D_s for the three models computed from (8) and the "Cygnus A" red-shifts of Table I. It is, of course, possible to equate l_s with D_s since the red-shifts of NGC 1275 and Cygnus A are relatively small. Thus, the entries of Table II can be used to calculate distances in light-years or parsecs as soon as some accuracy in the distances of these two standard sources has been attained. Meanwhile, the entries of Table II and (8) show that, if the red-shift of a Class II radio source is large and its luminosity-distance D is equated to the distance l computed on the static Euclidean universe hpothesis, then D will be underestimated if $x > -1$ and over-estimated if $x < -1$.

High-Altitude Measurements of X Rays and Far Ultraviolet Radiation*

HERBERT FRIEDMAN†

Summary—**Since 1946, the Naval Research Laboratory has conducted basic research in the physics of the upper atmosphere by means of high-altitude rockets. The program has emphasized all areas of research, including atmospheric structure and composition, the ionosphere, airglow and aurora, meteors, cosmic rays, and rocket astronomy. In the last area, which includes X ray and ultraviolet radiation measurements, NRL scientists have contributed a major portion of the experimental information available today. These comprise all the existing data on solar X rays, the X ray and ultraviolet emissions of solar flares, the first spectrogram of the sun covering the ultraviolet region below 3000 A and subsequent extensions of the spectrum into the extreme ultraviolet, the first quantitative measurements of solar Lyman-α, and the discovery of ultraviolet nebulosities and the Lyman-α glow of the night sky. A recent success in photographing the profile of Lyman-α with very high resolution opens the way to the use of optical resonance absorption as a gauge of atmospheric composition. This method may prove to be a most powerful technique for analysis of the very high atmosphere, well beyond the range of satellite drag measurements. The purpose of this paper is to describe the experimental approach used in accomplishing the radiation measurement program just outlined.**

INTRODUCTION

BY FAR the major portion of the effort that has gone into rocket astronomy has been directed toward studies of solar radiation and solar terrestrial relationships. Our weather, plant life, and natural energy sources such as coal, oil, wind, and water power are all derived from the sun. The total flow of solar energy appears to be very nearly constant, and the source of variability in weather may be largely attributed to differential heating of oceans and continents and seasonal changes due to the inclination of the earth's axis rather than to any variability in solar output. There is considerable evidence, however, that certain large-scale terrestrial weather patterns are correlated with solar weather, perhaps through the medium of invisible radiation in the form of ultraviolet rays, X rays, or particles. The relationship between solar phenomena and the quality of radio communications is very direct. The ionosphere waxes and wanes in direct response to the flood of solar ionizing radiation. Long-term observations of critical frequencies of radio reflections show a remarkable correlation with sunspot number. It has now been established by rocket experiments that variations in X ray and ultraviolet emissions are also associated with sunspots and the fundamental processes involved in production of the ionosphere are fairly well understood. From an astrophysical standpoint, the rocket observations have greatly advanced our knowledge of the origins of the various types of radiation in the solar atmosphere, and may ultimately contribute to our understanding of the sources of energy available near the surface of the sun.

ROCKET SPECTROSCOPY

Spectroscopy became important to astronomy when photographic film was invented about 100 years ago. Since then, almost all experimental techniques in astronomy have been based upon the use of photographic registration. It is not surprising, therefore, that the first instrument developed for rocket spectroscopy was a concave grating spectrograph in which the film, after exposure, was wound inside a light-tight cassette made of steel. The film had to be

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recovered after impact and subsequently developed. After early successes had extended the known solar spectrum into the near ultraviolet,[1] it became clear that highly accurate pointing controls and photoelectric detection techniques would be necessary to measure the shorter wavelengths of the ultraviolet and the X-ray end of the solar spectrum. Considerable success has been achieved in both the instrumentation of sun-seeking devices and the development of electronic radiation detectors.

If a spectrograph is fixed to the body of a ballistic rocket, roll and yaw may reduce the effective exposure time by a factor of 10 to 100 times. To compensate for the inherent instability of the rocket as a platform for a spectrograph, the early instruments were designed with extremely wide useful fields of view and succeeded in recording spectra down to 2100 A. The first pointing control was a single axis sun follower compensating only for the rocket spin about its long axis. In recent years, a sun-following biaxial pointing control described by Stacy, Stith, Nidey, and Pietenpol[2] has been used to compensate for yaw as well as roll with considerable success. By means of a servo system directed by a photoelectric angular sensing device, the spectrograph is kept pointing at the sun for a time of the order of 5 to 10 seconds with an accuracy of 1 minute of arc. Over a period of 3 to 5 minutes, the error does not exceed 5 to 10 minutes of arc. With this pointing device, the Lyman-α line of hydrogen at 1215.7 A was first photographed in 1952.[3] Since then, the limit has been steadily pushed to shorter wavelengths until it now appears feasible to record even the X-ray spectrum. Fig. 1 is a photograph of a spectrograph mounted on a biaxial pointing control designed for the Aerobee rocket. At rocket take-off, the entire spectrograph housing is protected by the rocket's nose cone. At a height where air drag becomes small, protective panels are jettisoned and the biaxial pointing control swings the spectrograph out so that the photoelectric sensing eyes may seek the sun. Correction for the rocket's roll was accomplished by rotating the entire nose section about the rocket axis. At the same time, correction for the yaw is achieved by permitting the spectrograph to swing in trunnions attached to the rotating nose section.

Imaging the Sun in Ultraviolet Light

The face of the sun presents an ever-changing pattern of visible events. Large numbers of phenomena are observed. Among the more familiar features are sunspots, plages, prominences, and flares. These phenomena are interrelated in somewhat the same fashion that meterological processes combine to produce terrestrial weather.

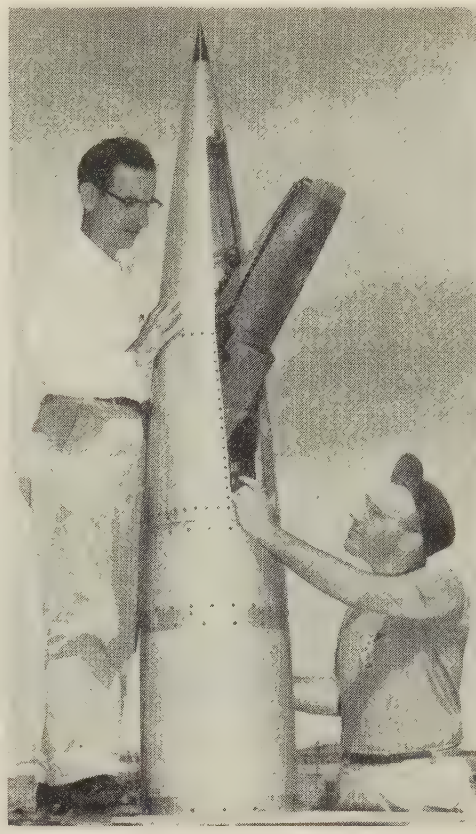

Fig. 1—Rocket spectrograph mounted on biaxial sunfollower.

By analogy, solar physicists refer to variable solar features as "solar weather." In spite of the great amount of detail observed in visible light, however, it is difficult to extrapolate to a picture of the sun in invisible wavelengths. It is essential to be able to record images of the sun in the range of ionizing wavelengths including Lyman-α, the helium resonance lines at 584 A and 304 A, and in various X-ray wavelengths.

To photograph from a rocket requires even more precise pointing than that developed for the spectrograph. Only with extremely fast optics is it possible to stop the residual movement in the pointing device and to obtain sharp pictures. The photograph shown in Fig. 2 is the first detailed image recorded in the ultraviolet at the wavelength of Lyman-α (1215.7 A), the principle resonance line of atomic hydrogen. The Lyman-α camera is diagramed in Fig. 3. This instrument was the result of four years of development at NRL by Tousey, Purcell and Packer.[4] The only optical material which transmits the Lyman-α wavelength is lithium fluoride. An earlier camera, designed by Rense of the University of Colorado and utilizing prism optics, yielded a comparatively crude image but indicated a much higher speed would be necessary to obtain clear detail. This increased speed was achieved through the development of very highly reflecting surfaces[5] which per-

[1] W. A. Baum, F. S. Johnson, J. J. Oberly, C. C. Rockwood, C. V. Strain, and R. Tousey, "Soler ultraviolet spectrum to 88 kilometers," *Phys. Rev.*, vol. 70, pp. 781-782; November, 1946.

[2] D. S. Stacey, G. A. Stith, R. A. Nidey, and W. A. Pietenpol, "Rocket-borne servo tracks the sun," *Electronics*, vol. 27, pp. 149-151; January, 1954.

[3] W. A. Rense, "Intensity of Lyman-alpha line in the solar spectrum," *Phys. Rev.*, vol. 91, pp. 299-302; July, 1953.

[4] D. M. Packer, J. D. Purcell, and R. Tousey, "Lyman-alpha photographs of the sun," *Nature*, vol. 184, pp. 8-10; July, 1959.

[5] G. Hass and R. Tousey, "Reflecting coatings for the extreme ultraviolet," *J. Opt. Soc. Amer.*, vol. 49, pp. 593-602; June, 1959.

Fig. 2—Photograph of the sun in the wavelength of Lyman-α (1215.7 A) March 13, 1959.

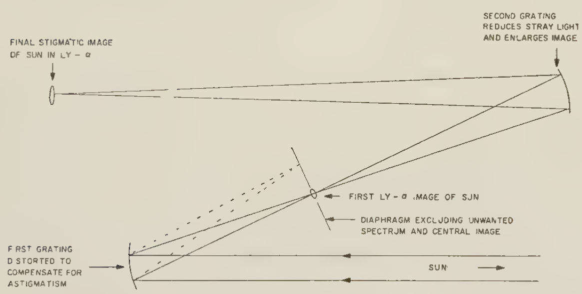

Fig. 3—Diagram of Lyman-α solar disk camera.

mitted the use of mirror optics in the NRL instrument. These were not ordinary mirrors, however, but were diffraction gratings-parabolic mirror surfaces ruled with 15,000 lines to the inch. The rulings caused the intense visible light from the sun to be thrown out of the camera leaving only the monochromatic Lyman-α radiation to form the solar image. The combination of high-speed optics and the very intense emission of Lyman-α radiation from the sun made it possible to obtain satisfactory film densities in exposure times of 1/50 of a second.

At shorter wavelengths, reflectivities deteriorate rapidly and it appears necessary to replace photographic registration with more sensitive electronic detection. Suitable detection devices will be described below. It appears to be entirely feasible to place a detector at the focus of a parabolic mirror telescope and to wobble the mirror so as to scan the solar image across the detector. If the wobbling movement is in the form of a TV raster, the response of the detector can be telemetered to ground where a multiline image can be reproduced. Such techniques may make it possible ultimately to transmit daily solar weather maps in invisible ultraviolet and X rays from satellite observatories.

Photoelectric Sensors for Ultraviolet and X Rays

In parallel with its spectrographic program, the NRL developed a series of narrow-band photoelectric detectors capable of isolating important regions of the ultraviolet and X-ray spectrum. The information from these sensors is telemetered continuously during the flight of a rocket and traces the atmospheric absorption characteristic of each specific radiation band to the peak of the flight. Not only do such experiments measure the solar flux, but they identify the region of the atmosphere which is affected. If the absorption is characteristic of a particular constituent, the variation of intensity versus altitude is a measure of the particle density of that constituent. This technique has been used to give the only experimental evidence of the variation of molecular oxygen with altitude in the E and F1 regions of the ionosphere. At X-ray wavelengths where absorption is essentially independent of composition, the radiation technique is a direct measure of atmospheric density.

Experiments with narrow-band photodetectors were begun by the NRL in 1949.[6] In the decade between then and now, all the available information on solar X-ray fluxes below 100 A units has come out of the continuing program of upper air research at NRL. In a similar way, the NRL program obtained the first quantitative measures of the important Lyman-α emission and a major portion of all subsequent data on its variation over a decade of observations.[7] In three major programs to study the emissions of solar flares, Project Rockoon (1956), Project Sunflare I (1957), and Project Sunflare II (1959), narrow-band photodetectors have been used to measure the X-ray and ultraviolet emissions accompanying solar flares.[8]

Restriction of bandwidth in gaseous ionization chambers and photon counters may be accomplished by selecting combinations of ionizable gases and window materials with well defined transmission limits. Table 1 lists various windows and gas fillings together with the ranges of spectral response.

At X-ray wavelengths, use is made of characteristic atomic absorption edges of thin foils and films to define a short wavelength cutoff. For example, 8 A marks the K edge of aluminum and 24 A the K edge of carbon, which is the major constituent of Mylar and Glyptal plastic films. On the long wavelength side, the transmission falls in-

[6] H. Friedman, S. W., Lichtman, and E. T. Byram, "Photon counter measurements of solar X-rays and extreme ultraviolet light," *Phys. Rev.*, vol. 83, pp. 1025-1030; September, 1951.

[7] E. T. Byram, T. A. Chubb, H. Friedman, J. E. Kupperian, Jr. and R. W. Kreplin, "Intensity of solar Lyman-alpha and adjacent ultraviolet emission lines," *Astrophys. J.*, vol. 128, pp. 738-741; November, 1958.

[8] H. Friedman, "Rocket observations of the ionosphere," Proc. IRE, vol. 47, pp. 272-279; February, 1959.

TABLE I
NARROW-BAND PHOTON COUNTERS AND IONIZATION CHAMBERS

Window	Thickness	Ionizable Gas	Response Band (Angstroms)
Beryllium	0.005 inch	neon	1– 8
Aluminum	0.00025	neon	8– 18
Mylar	0.00025	helium	44– 60
Glyptal	0.00006	helium	44– 100
Lithium fluoride	2 mm	nitric oxide	1100–1340
Calcium fluoride	2 mm	nitric oxide	1225–1340
Sapphire	1 mm	xylene	1425–1500

versely as the cube of the wavelength. In an X-ray photon counter or ion chamber, the ionization current is derived from photoelectric absorption in the gas. To avoid response to wavelengths very much shorter than the K edge of the filter, where transmission again becomes appreciable, the gas is chosen from one of the lighter gases such as helium or neon, which are transparent to the shorter wavelengths but absorb strongly at wavelengths longer than the K edge of the filter.

Gaseous ionization detectors operating in the ultraviolet region above 1000 A exhibit a spectral response compounded of: 1) a long wavelength surface photoelectric effect with a threshold above 2000 A for most metals; 2) an internal photoelectric effect confined to wavelengths below 1500 A; and 3) photoionization of a gas. The yield of the long wavelength surface photoelectric effect is small, of the order of 10^{-5} to 10^{-7} electrons per quantum. For most metals a new threshold appears at a wavelength in the far ultraviolet, usually between 1000 and 1400 A at which the yield may multiply abruptly by as much as 1000 times. Finally, most gaseous molecules have thresholds for photoionization below 1500 A and reach such high cross sections for photoionization that yields of close to 100 per cent are possible.[9]

A wide variety of filter materials and gas absorbers are available for the construction of narrow-band photon counters. Tables II and III list the transmission properties of certain solids and gases. How to combine the various properties to produce a narrow-band photon counter may be illustrated by specifying the selection of window and gas filling for a tube sensitive to wavelengths near 1450 A. The window may be synthetic sapphire which is transparent down to a short wavelength limit of 1425 A. Xylene vapor is included because it has a photoionization threshold at 1500 A. Nitric oxide is nonphotosensitive above 1350 A but is added to the gas mixture because it effectively captures all electrons released by long wavelength photoelectric effect on the cathode surface. The combination of a sapphire window and a gas mixture consisting of 44 mm of nitric oxide, 0.5 mm of xylene, and 650 mm of helium produces a spectral response which is confined to the region between 1425 A and 1500 A. If used to measure solar radiation above the atmosphere, this tube responds strongly to the solar flux of about 3×10^{10} quanta cm^{-2} s^{-1}, between 1425 and 1500 A, while rejecting the photoelectric contribution of about 5×10^{12} quanta cm^{-2} s^{-1}, between 1500 and 2000 A. This spectral response characteristic is ideal for measuring the absorption of solar radiation by molecular oxygen in the dissociation continuum.[10]

Between 100 A and about 1100 A only the very thinnest films transmit appreciably and it is difficult to prepare windows that can meet the requirements of vacuum tightness and mechanical strength. A nitrocellulose film about one thousand angstrom units thick transmits about 44 per cent at 46 A and about 17 per cent at 220 A. An evaporated film of pure aluminum 500 A thick begins to transmit at 830 A on the long wavelength side and remains fairly transparent down to the L III edge at 170 A. Purcell and Tousey have suggested using such a film over a layer of flourescent material coated on the window of a photomultiplier tube to provide detection of wavelengths within the transmission range of the aluminum film. It is also possible to dispense completely with the window material and to use photon counters or ionization chambers of the free-flow type. The solar spectrum is sufficiently intense that measureable responses could be obtained through a window as small as 0.005 inch in diameter. A small flask of gas may be used as a reservoir to maintain constant pressure within the photon counter as the gas flows out through the window orifice. By selecting the fill gas from the rare gases, it is possible to control the long wavelength threshold in a number of steps. The ionization potentials of helium, neon, argon, krypton, and xenon are 507, 577, 791, 890, and 1027 A respectively. A helium flow counter at low pressure makes an excellent monitor of the He II resonance line at 304 A.

The simple vacuum photocell would be an effective detector for the 100 to 1100 angstrom range if it were possible to suppress the long wavelength response. T. A. Chubb of NRL has succeeded in preparing tubes with evaporated lithium fluoride surfaces that exhibit yields of 40 per cent at 585 A and less than 1 per cent at Lyman-α. Hinteregger of the Air Force Cambridge Research Center has applied a method of retarding potentials to scan the photoelectron energy distributions between Lyman-α (1216 A) and He II (304 A). If it is desired to use secondary emission multiplication after the photo-surface, the dynodes must be prepared of materials which do not respond to longer wavelengths. A silver magnesium surface is insensitive to light of wavelength longer than 3000 A and still provides secondary emission multiplication factors in excess of 2. A multiplication surface consisting of a tin oxide layer on glass has recently been developed by the Bendix Research Laboratories which exhibits almost no photoelectric response at wavelengths longer than Lyman-α.

Photon counters can be produced with sensitivities of

[9] T. A. Chubb and H. Friedman, "Dissociation of Oxygen in the upper atmosphere," *Rev. Sci. Instr.*, vol. 26, pp. 493-495; May, 1955.

[10] E. T. Byram, T. A. Chubb, and H. Friedman, "Photon counters for the far ultraviolet," *Phys. Rev.*, vol. 98, pp. 1594-1597; June, 1955.

TABLE II

Transmission Characteristics of Solid Material in the Vacuum Ultraviolet

Material	Approximate Filter Thickness mm	Wavelength Regions in Which Transmission Exceeds 10 Per Cent (Angstroms)	Wavelength Regions of Less than 1 Per Cent Transmission (Angstroms)	Character of Short-wave Cutoff
LiF*	0.4	>1050	<1030	Sharp with moderate absorption up to 1300 A
X-rayed LiF	1	1200–2200, >2800	2300–2700, <1175	Depends on *F* center density
X-rayed and thermally bleached LiF	1	1100–2000, >2400	2100–2300, <1075	Similar to uncolored LiF
CaF*	3	>1220	<1215	Sharp
Evaporated film CaF_2 on LiF base		>1200	<1150	Good transmission at $\lambda > 1200$ A compared to that for $\lambda 1150$–$\lambda 1200$ A
Sapphire (synthetic)†	0.5	>1425	<1415	Sharp
Fused quartz‡	1	>1560	<1525	Gradual. General reduction of UV transmission by X-ray irradiation
Topaz (natural)	1	>1550	<1525	Sharper than fused quartz
Gypsum (natural)	1	>1620	<1600	Similar to topaz
NaCl*	1	>1710	<1700	Sharp
KCl*	1	>1750	<1740	Sharp
KBr*	1	>2010	<2000	Sharp
Teflon	0.006	>1700	<1660	Gradual-considerable loss of light due to scattering
SrF_2‖	0.88	>1300	<1270	Sharp
NaF*	1.37	>1310	<1276	Sharp

* Harshaw Chemical Co.
† Linde Air Products.
‡ Central Scientific Co.
‖ Optovac Co.

TABLE III

Transmission Characteristics of Gas Filters for the Vacuum Ultraviolet

Gas	Approximate filter thickness in cm (reduced to NTP)	Regions of useful transmission (Angstroms)	Regions of high opacity (Angstroms)
O_2	6.0	1102–1110, and narrow transmission bands centered at 1124, 1158, 1166, 1189, 1216; >1800	Other wavelengths shorter than 1750
CH_3Cl	0.1	1425–1460, >1850	1475–1610, <1420
CH_3Br	0.05	1525–1575, >1800	1610–1775, <1520
CCl_2F_2	0.0025	1200–1230, >1375	1234–1325, <1195
CS_2	0.05	About 10 transmission bands between 1530 and 1780, >2200	1800–2100, <1520
NH_3	0.1	About 10 transmission bands between 1450–1700; >2150	1700–2050, <1425
N_2O	0.025	1200–1220, >1530	1220–1350, <1190

Gas	Approximate filter thickness in cm (reduced to NTP)	Regions of useful transmission (Angstroms)	Regions of high opacity (Angstroms)
SO_2	0.1	1625–1750, >2250	1800–2150, <1590
H_2S	0.1	1600–1700, >2300	1800–2200, <1575
CO_2	0.5	1175–1250, >1650	1300–1550, <1150
CCl_4	0.0025	1160–1200, >1550	1220–1330, <1150
Cl_2	0.1	About 12 transmission bands between 1170 and 1310. One band transmits Lyman radiation; <1450	1340–1420, <1170
CH_4	0.025	>1400	<1375
C_3H_8	0.1	>1600	<1575
$(CH_3)_3CH$	0.1	>1060	<1640
C_2H_4	0.025	>1850	<1750

10^{-9} erg cm^{-2} s^{-1} at a signal-to-noise ratio of 10. Such detectors have made it possible to initiate the science of rocket astronomy with unguided ballistic rockets.[11] Fig. 4 is a contour map of a portion of the sky in the neighborhood of Orion mapped by a photon counter sensitive to the band 1225 to 1350 A. The sensitivity of the detector can be appreciated when it is pointed out that the flight time above the absorbing terrestrial atmosphere was less than 2 minutes and that the tube was fixed to the skin of a rocket that was spinning and precessing freely without constraints.

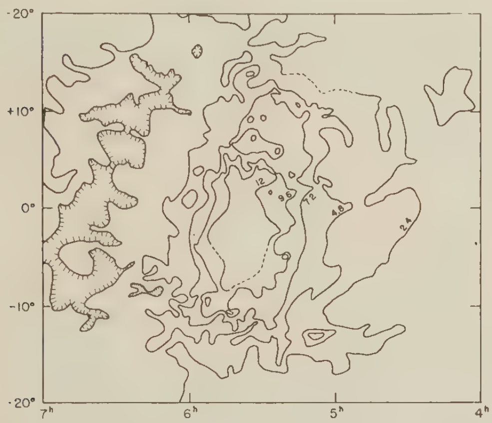

Fig. 4—Ultraviolet nebulosity in the region of Orion. Isophotes of 1300-A radiation; values of surface brightness in units of 10^{-4} ergs/cm^2.

Atmospheric Structure

Second only in fundamental importance to mapping the spectrum of the sun and other celestial sources is the observation of the absorption of such radiation in the terrestrial atmosphere. The significance of the various ultraviolet and X-ray wavelengths for the production of the ionosphere has already been mentioned above and is treated extensively in the literature.[12] Using the sun as a light source and measuring the variation in atmosphere attenuation with altitude, it is possible to determine the height distribution of all the major and some minor constituents of the atmosphere to its outermost limits. One of the earliest successes of rocket spectroscopy was the detection of the ozone distribution up to 70 km. The attenuation of Lyman-α is a gauge of the O_2 concentration in D region and may also provide a means of determining H_2O at those altitudes. Molecular oxygen has been traced to 170 km by observing the absorption of solar 1500-A radiation and the total atmospheric density has been measured to 160 km by using X rays in the 44- to 60-A band. Spectra taken at a height of 200 km show no evidence of Lyman-γ, which appears to be absorbed by molecular nitrogen. It seems likely that this spectral line will provide a good measure of molecular nitrogen at heights above 200 km.

Although the above examples are impressive evidence of the power of the optical approach, a high-resolution spectroscopic technique developed by Purcell and Tousey at NRL points the way to an extension of the sensitivity and selectivity of optical absorption measurement by several orders of magnitude. The cross sections involved in the above-mentioned examples fall in the range of 10^{-20} to 10^{-17} cm^2 and are associated with processes of ionization and dissociation. In resonance absorption, however, the cross section may be greater than 10^{-13} cm^2 in the center of the absorption line. In principle, it should be possible to determine the concentrations of hydrogen and various other atmospheric constituents to heights of several thousands of kilometers by measuring the amount of self reversal in the core of the appropriate solar emission line as a function of altitude of a vertical rocket probe.

At the temperature that may exist in the very high atmosphere, a resonance absorption line should have a width of the order of 0.1 A or less. Obviously, the measurement of the profile of such a line requires more than an order of magnitude improvement in resolving power over the spectrographic techniques that have previously been applied in rockets. Purcell and Tousey approached the problem by using a 12,000 line/mm grating of 50-cm radius in the thirteenth order of diffraction, since resolving power is directly proportional to order of diffraction. The theoretical resolving power was 266,000, corresponding to approximately 0.005 A at Lyman-α and the dispersion of the instrument was 2.6 mm/A. In the flight experiment, the spectrograph appeared to resolve 0.03 A and showed a deep narrow core of the order of 0.05-A width in the center of the solar emission line about 0.7 A wide. From this profile, it was deduced that the total neutral hydrogen content per square centimeter column between the rocket at 200 km and the sun was between 10^{12} and 10^{13}.

Similar measurements may be made on atomic oxygen and atomic nitrogen resonance lines. If the photographic film is replaced by a photoelectric sensor, the profile may be scanned at various altitudes and telemetered so that it is possible to determine the atomic concentration vs altitude. Such instrumentation is now being developed for flights in small rockets such as the Javelin and Journeyman, capable of reaching altitudes of 1000 to 2000 miles.

Although using a high order of diffraction to obtain resolution has given encouraging results, an instrument capable of much higher resolution is the echelle spectrograph. Such a grating has a higher blaze efficiency, greater light gathering power and can be obtained with extremely low ghost intensities.

Radiation Monitoring Rockets and Satellites

Returning to consideration of the simple narrow-band photometers, it is clear that much valuable information on solar variability and atmospheric structure can be ob-

[11] T. A. Chubb, E. T. Byram, H. Friedman, and J. E. Kupperian, Jr., "The Threshold of Space," Pergamon Press, London, Eng., p. 203; 1957.

[12] R. J. Havens, H. Friedman, and E. O. Hulbert, "The Ionospheric F2 Region," The Physics of the Ionosphere, Rept. of 1954 Cambridge Conference, p. 237.

tained by their use. In the author's opinion, observations of the attenuation of solar radiation in the atmosphere constitute one of the most direct sources of information on atmospheric structure. It is desirable to devise basic photometer packages for small rockets that can be flown in a latitude survey from the Arctic to the Antarctic and used in synoptic studies to observe diurnal and seasonal variations.

Instrumenting a satellite with a variety of narrow-band photometers covering as many significant wavelength regions as possible is also highly desirable. Observations could be made of the sun, the night airglow, day airglow, and auroral light.

Consider the possible makeup of such a radiation monitoring satellite as conceived by the author's colleagues at NRL. The solar photometers would consist primarily of ion chambers and photocells. Most of the X-ray detectors would be vacuum tight ion chambers fitted with thin windows and utilizing inert gas or nitrogen fillings. In the spectral bands where no suitably transparent windows are available, for example between 100 and 1050 A, low-pressure free-flow ion chambers could be used. These ion chambers would be supplied with vapor obtained from reservoirs carried in the satellite. A free-flow ion chamber would probably be used in the 1425- to 1500-A band where photochemical decomposition of the ionizable gas is particularly severe. The longer wavelengths, for example those between 1600 and 5000 A, would be monitored by photoemissive cells containing surfaces of CsI, Rb_2Te, and Cs_3Sb. In the infrared, a photoconductive cell may be used. Aspect information would be obtained on the basis of signals furnished by an optical sensor which measures the angle between the satellite spin axis and the sun. The addition of the magnetic aspect system would provide a measure of the angle between the satellite spin axis and local magnetic field. The combination of solar aspect and magnetic aspect permits a unique determination of the satellite aspect at any instant of time.

The general method of making measurements would be based on utilization of satellite spin as a means of modulating the incident radiation fluxes. The satellite could be designed with a major moment of inertia corresponding to the direction of spin, that is, in the form of a flat cylinder or octagon with the mass concentrated near the rim. All the solar detectors would be mounted looking out perpendicular to the axis of spin. All night-time and day airglow detectors would be paired at diametrically opposite positions and directed at 45° to the spin axis. A nearly polar orbit would permit the most interesting variety of scanning geometries for both the observation of atmospheric structure and determination of the movements of the airglow.

All of the required photometry could be accomplished by a collection of about 50 sensors. The tracking transmitter would be similar to the Vanguard model radiating 10 mw at 108 mc. Telemetry requirements would be satisfied by a power amplifier radiating 4 watts on command and modulated by 5 subcarrier oscillators. The required power for all circuit functions would be obtained from 430 cm² of solar batteries distributed around the periphery of the spinning satellite. The total weight of the satellite need not exceed 200 pounds, and a satisfactory orbit would require a perigee greater than 350 miles and an apogee less than 600 miles. The spin frequency should be about 0.5 rps.

Consider the scientific data that could be provided by a radiation monitoring satellite.

Solar Emissions

The continuous recording of X-ray and ultraviolet radiations would permit direct correlations of ionospheric behavior with the effective solar radiations and relate the invisible radiations to visible phenomena such as flares, surge prominences, and levels of plage activity. Relationships between solar radiation and the airglow and aurora would also be revealed.

Attenuation of Solar Radiation

Measurements of the attenuation of various solar bands during passage of the satellite into or out of the earth's shadow should provide information about the vertical distribution of atmospheric constituents such as O_3, O_2 and O. With a polar orbit, these data would be obtained initially at latitudes near the north and south poles and at all longitudes. As the earth moves around the sun in its orbit, a great variety of attenuation geometries would become possible at all latitudes. The data would be limited somewhat by the fact that the sun has an angular diameter of half a degree. However, the resolving power in altitude would permit significant world-wide comparisons of vertical distributions.

Day Airglow

The earth should appear to be black in the wavelength region of ozone absorption 2400 to 2700 A except for radiation by O_2. It is of interest to see if this is really true. Strong airglow emissions expected in the daytime are 3914 A from N_2^+, 7619 from O_2, 6300 from OI and 5893 from Na. All of these are expected to show strong enhancement near the horizon. The heights of these layers could be mapped on a world-wide basis.

Zodiacal Light

A detector, which measures a broad band of visible light excluding the brightest airglow emissions, can provide data on the zodiacal light in the ecliptic plane. The earth itself would provide the necessary eclipsing disk before the sun.

Night Airglow

There are a number of characteristics of the night airglow that could be determined with photoelectric photometers. First, the waves and variations that are known to exist in the airglow could be mapped. They are thought to be produced by waves in the circulation of the upper atmosphere, and such a map would give important data bearing on the circulation pattern. Each photometer would scan a curved belt, broadest near the equator and narrowing somewhat at higher latitudes. Each orbit would cover successive

strips of the earth about 30° apart in longitude. Since the earth would be scanned always at the same local time, the data would be free from diurnal effects. A second result would be the height of the various airglow layers, from a measurement of the zenith angle of the maximum in luminosity. A third result would be the study of twilight enhancement for the various emissions, when the satellite passed into twilight at high latitudes, both north and south. The measurements would cover the permanent artic twilight regions as well as the transitory diurnal twilight.

Aurora

The photometry satellite offers the possibility of directly comparing the Aurora Borealis and Aurora Australis. The distribution could be plotted relative to the earth's magnetic poles. Correlations could be sought between observations of solar variations and changes in the auroras. These might be expected to be most conspicuous for the auroral Hα line and for X rays in the 10 to 150 kev range. The world-wide distribution for Hα, Lyman-α, X rays, and the usual auroral emissions could be correlated.

X-ray and Lyman-α photometer packages have been prepared by NRL for several Vanguard attempts and for the ABMA International Geophysical Year heavy payload. Only Vanguard III succeeded in orbiting and it carries just one channel of X-ray information. These past attempts represent only minimal experiments and it is to be hoped that full-fledged photometry satellites of the type sketched above may soon be included in the national space effort. The experimental background for design of the photometric sensors derives directly from past rocket experiments. In applying these techniques to satellite instrumentation, much more severe specifications are imposed on the stability and life of the sensors, but no unsurmountable difficulties seem to bar the way toward satisfying all the requirements.

A Gas Cell "Atomic Clock" as a High-Stability Frequency Standard*

MAURICE ARDITI†

QUARTZ crystal oscillators have been developed to a high degree of accuracy. Stability of 3×10^{-9} per day or better has been achieved. These oscillators, however, require an aging period of several months. This basic defect can be greatly alleviated by locking the crystal oscillator to the center frequency of a stable atomic transition through a servo-mechanism system. This is the general principle which is used in the atomic beam frequency standard and also in the present gas cell standard. Moreover, a gas cell type of "atomic clock" is quite easily adaptable to a small and simple package, and this is advantageous for airborne operation.

Following the work pioneered by R. H. Dicke and T. R. Carver of Princeton University, a gas cell frequency standard has been developed by ITT Laboratories and recently tested for accuracy and stability.[1] Some of the results obtained in these tests are reported here.

General Description of a Gas Cell Frequency Standard

A simple gas cell frequency standard [1] will include the following components (see Fig. 1): an oscillator of very

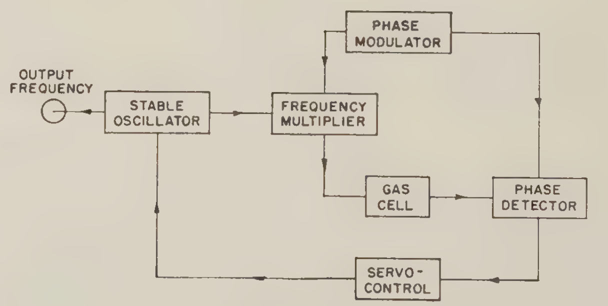

Fig. 1—Simple gas cell atomic frequency standard.

good short-term stability (crystal oscillator and multiplier chain), a phase modulator, a gas cell where the atomic transition takes place, a phase sensitive amplifier-detector, and a feedback-loop servo locking the crystal oscillator to the resonant frequency of the atomic transition. The microwave energy is frequency modulated at a low rate and with a small frequency excursion, thus obtaining the derivative of the resonance line at the output of the phase detector. In order to lock the oscillator to the atomic resonance, the signal output of the phase detector is fed back, in proper phase, to an element controlling the frequency of the crystal oscillator, through an amplifier and servo-control system.

For an atomic frequency standard of high stability and high accuracy, the following three characteristics are essential.

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† ITT Labs., Nutley, N.J.
[1] Work was supported in part by the ONR under Contract No. Nonr-2553(00) NR 374-901.

1) The center frequency fo of the atomic transition should be very stable, *i.e.*, independent of electric or magnetic fields, independent of pressure, temperature, humidity, mechanical tuning, etc.

2) The width of the atomic resonance should be as narrow as possible.

3) The signal-to-noise ratio of the detection should be as high as possible.

These conditions can be met in a gas cell frequency standard using the alkali metal vapors such as sodium, rubidium or cesium. The considerations which make this approach suitable are discussed briefly in the following paragraphs. More detailed information is contained in the literature. [1], [5]

The atomic transition of interest is the 0,0 magnetic dipole transition in the hyperfine levels in the ground state of the alkali metal vapors, and is based on the relative orientation of the spin of the valence electron as compared to the spin of the nucleus. This magnetic transition is not seriously affected by electric fields and the dependence of the frequency upon the magnetic field is given by a quadratic term. For example, in the case of Cs^{133},

$$fo = 9192.63 \times 10^6 + 426\, H^2 \text{ cps},$$

where H is the magnetic field in oersteds. This means that if a magnetic field of about 0.1 oersted is maintained constant to within 10 per cent within the volume of the gas cell, then the frequency will be stable to 1 part in 10^{10}. This magnetic field condition can easily be achieved with a good magnetic shield. However, the presence of a buffer gas in the cell can produce pressure and temperature shifts of the hyperfine resonance frequency, as discussed in the next paragraph.

In order to reduce the broadening of the atomic resonance due chiefly to Doppler effect, Dicke suggested the introduction in the cell of a nonmagnetic buffer gas such as argon, neon, xenon, etc. With this method, line widths as narrow as 20 cycles have been obtained with RB^{87} at room temperature, giving a Q of over 300 million. [2] However, the buffer gases produced a shift of the center frequency of the hyperfine transition, and this shift is a linear function of the pressure. This effect could be a serious drawback for a frequency standard. Fortunately, it has been found that the lighter gases, hydrogen, helium or neon, for example, produce a shift toward the higher frequencies, whereas the heavier gases such as argon, krypton, xenon, produce a shift toward the lower frequencies (see Fig. 2), and that a proper mixture of these gases can produce a very small frequency shift within a large range of pressure or temperature variations. [4] For example, in the case of $cesium^{133}$, a minimum of pressure shift has been obtained with a mixture of argon (75 per cent) and neon (25 per cent).

The signal-to-noise ratio of the detection is proportional to the unbalance in the populations of atoms in the energy levels between which the transition is observed. This ratio can be increased considerably by using the "optical pumping" method as suggested by Kastler, Dicke, Dehmelt and their co-workers. [3] In this method, by irradiating the alkali-vapor with resonant light, a large population difference can be produced. Furthermore, an interesting application of the orientation of the alkali atoms by optical pumping is the use of this phenomena to detect also the microwave transition by monitoring the intensity of the light emerging from the gas cell.

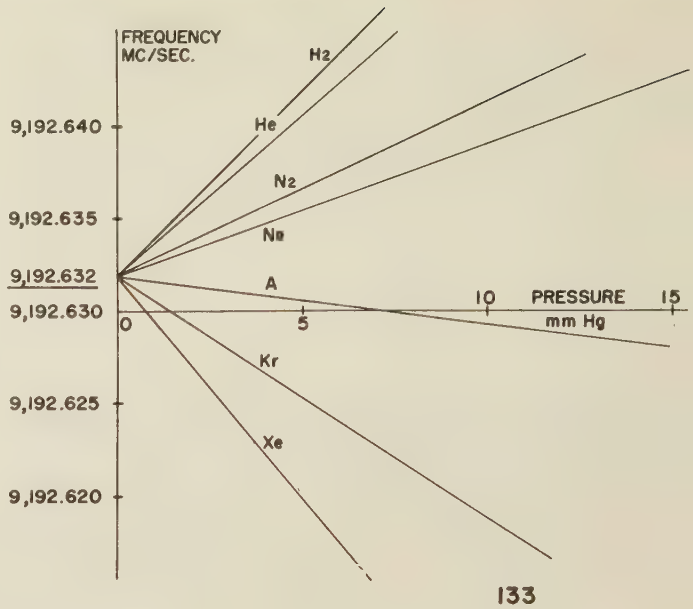

Fig. 2—Pressure shifts in Cs^{133}.

Gas Cell Atomic Clock Using Optical Pumping and Optical Detection

A schematic of the set-up is shown in Fig. 3. A sealed-off gas cell contains an alkali-vapor metal and buffer gases at suitable pressure and is maintained at the proper temperature, depending on the nature of the alkali metal used. A beam of resonance light from a resonance lamp is passed through the gas cell and is focused on a photocell. A homogeneous magnetic field of a few tenths of a gauss is produced in the region of the cell. The gas cell itself is placed in a microwave cavity resonating in the TE_{011} mode. The Q of the cavity is relatively low and, because of the optical detection, there is practically no frequency pulling due to the tuning of the cavity. Fig. 4 shows an exploded view of the cavity with the gas cell. The resonant lamp is of the electrodeless discharge type excited at 30 mc. The rest of the equipment, *i.e.*, photocell, audio-amplifier, phase detector, and servo, is of standard design.

The choice among sodium, rubidium, or cesium atoms depends mostly on the requirements of the packaging specifications, the temperature range of operation, and absolute accuracy. For example, Na^{23} atoms (fo = 1,771.6 mc) require a large size cavity and high temperature of operation (125°C), whereas Rb^{85} (3,035.7 mc), Rb^{87} (6,834.6 mc) or Cs^{133} (9,192.63 mc) can be packaged in smaller size cavities and will operate at lower temperatures. How-

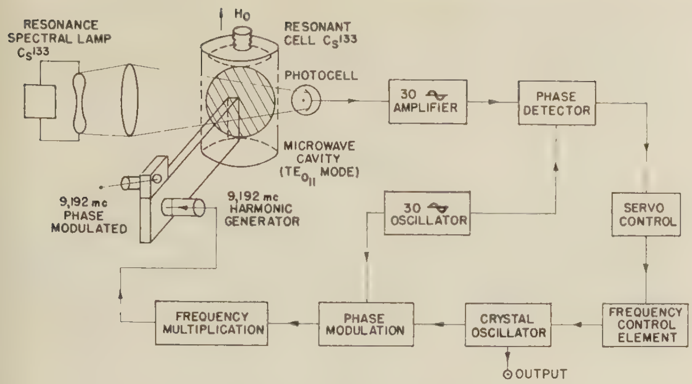

Fig. 3—Gas cell atomic clock using optical pumping and optical detection.

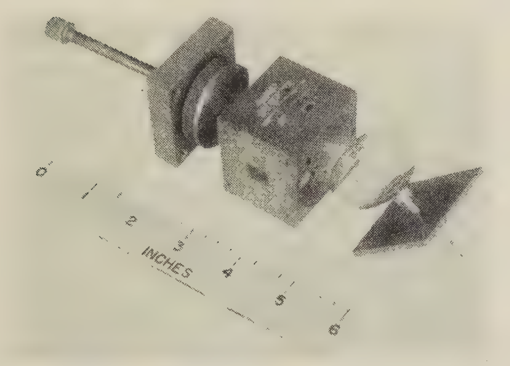

Fig. 4—Gas cell in microwave cavity, exploded view.

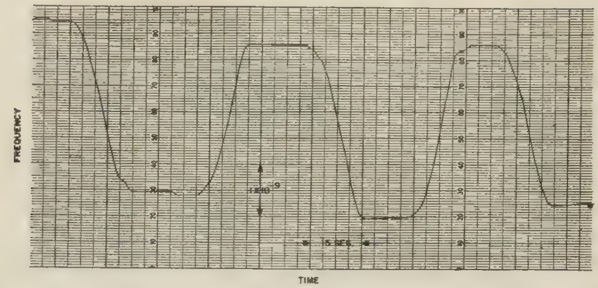

Fig. 5—Correction signal of servo system.

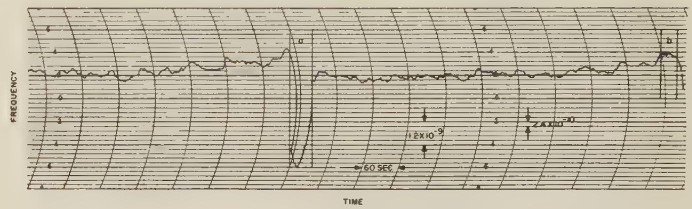

Fig. 6—Frequency of gas cell against N-R-L standard.

ever, because of the small pressure shift produced by pure argon in a sodium cell, it may be that sodium cell frequency standards can be reproduced with more absolute accuracy.

A breadboard model of a cesium gas cell frequency standard has been recently evaluated by comparing it with the frequency of ultra-stable oscillators at the Naval Research Laboratory, Washington, D.C. Fig. 5 shows the recording of the correction signal of the servo system as the frequency of the oscillator was intentionally pulled back and forth from the frequency corresponding to the cesium resonance. After a transient period, the error voltage reaches a plateau corresponding to a fixed and stable value of the frequency of the oscillator locked to the cesium resonance. Fig. 6 is a recording of the actual frequency difference between the standard and the gas cell frequency. At points a and b, the frequency of the crystal oscillator was intentionally changed by about 1 part in 10^9 after which the system reset itself on the lock of the atomic resonance. From the observation of such recordings, it was possible to deduce that the system had a short-time stability of ± 2 to 4 parts in 10^{10}, a long-time stability of ± 1 part in 10^{10}, and an accuracy of ± 3 to 4 parts in 10^{10}. Performances an order of magnitude better are predicted with careful control of environmental conditions. It is interesting to note that a gas cell frequency standard may be used more for its properties of long-term stability than for its absolute accuracy which may depend on the accuracy with which a mixture of buffer gases can be reproduced. For example, to obtain an absolute accuracy of 1 part in 10^9 to 1 part in 10^{10}, the accuracy of the buffer gas mixture has to be of the order of 10^{-2} to 10^{-3}. Comparatively, in an atomic beam apparatus, a mechanical stability of 1 part in 10^3 has to be maintained in order to obtain an absolute accuracy of 1 part in 10^{10} in the frequency standard.

Further development work on the gas cell is well underway toward the realization of a small portable unit with fully transistorized package for the electronics. When fully engineered, the unit could weigh less than 30 pounds and the power consumption could be less than 50 watts.

Applications

In addition to the general use of atomic clocks for high precision measurements of time intervals, various particular applications can be visualized for a small, portable gas cell frequency standard; some examples follow.

1) With such an inexpensive unit, numerous laboratories could have available a primary frequency standard, free of the vagaries of poor reception of radio broadcasts.

2) Even for systems, such as single sideband transmission systems, which require a moderate accuracy of 1 part in 10^8, the unit would be very valuable because it does not require resetting against a primary standard.

3) As an airborne unit, the gas cell frequency standard will be a very valuable aid to long-range navigation systems such as the Navarho system, where a stability and accuracy of 1 part in 10^9 is required.

4) In contrast to the Special Theory of Relativity. [7] the General Theory of Relativity cannot be considered satisfactorily verified by experiments. A test of the theory has been suggested using an atomic clock carried by a satellite orbiting around the earth. [6] Referring to Fig. 7, by comparing the rate τ of two atomic clocks, one on the earth, the other on a satellite, the following relation holds:

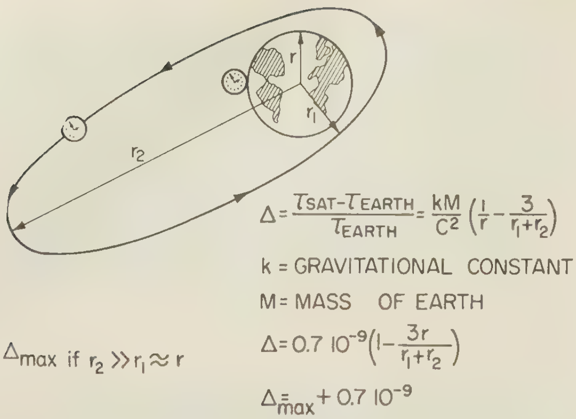

Fig. 7—Experiment to check theory of relativity.

$$\Delta = \frac{\tau_{sat} - \tau_{earth}}{\tau_{earth}} = \frac{kM}{C^2}\left(\frac{1}{r} - \frac{3}{r_1 + r_2}\right),$$

and for a highly eccentric orbit

$$\Delta = 0.7\ 10^{-9}.$$

This measurement is possible now with the stability of present atomic clocks.

Within the realm of the experiments of this space age, it may be that a small gas cell frequency standard carried by a satellite will soon bring about a decisive test of Einstein's General Theory of Relativity.

5) Using the same principles of optical pumping and optical detection of the Zeeman transition frequencies, the gas cell can be used also as a very sensitive magnetometer. [8]

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Precision Optical Tracking of Artificial Satellites*

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Introduction

THIS article concerns a study of the problem of instrumentation for precision optical position measurements of artificial earth satellites. Our[1] interest in this problem concerns the use of artificial satellites for precision experiments on gravitation.

In particular, the secular variation of the gravitational constant, G, (or active gravitational mass) proposed many years ago by Dirac may be observed using artificial satellite techniques. Such a change might be expected to amount to about one part in 10^{10} per year.[2] In addition, an annual variation in the period of the satellite would be a very sensitive indicator of a velocity dependence of the active gravitational mass of the earth. A variation in the active mass of order $(v/c)^2$ could yield an amplitude for the annual variation of the period of the satellite of one part in 10^8.[3] While a velocity independence is always assumed, there is presently little direct observational support for the assumption. Finally, a satelllte well above the earth's atmosphere in an orbit over the earth's poles may yield improved knowledge of the relativistic rotation of the perigee and the regression of the nodes having an origin in the earth's rotation.

A study of each of these effects requires extremely precise satellite position and time measurements. These measurements may be made by determining the satellite's position relative to axes fixed in the earth or relative to the star field. There is a substantial advan-

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[1] The following ideas are not wholly those of the authors, but in part due to the whole group: C. O. Alley, J. Brault, D. Brill, R. H. Dicke, J. Faller, W. F. Hoffmann, L. Jordan, R. Krotkov, S. Liebes, R. Moore, J. Peebles, J. Stoner and K. Turner.
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tage in determining position relative to the star field as this removes systematic errors associated with thermal tilt in telescope mountings.

In the techniques to be discussed, the background star field is recorded photographically. A photographic recording of the satellite position is employed when a sufficient number of photons is available. When the number of photons is few, it appears to be desirable to track the satellite photoelectrically with the telescope and to photograph the moving star field and perhaps also the satellite.

Of the various ways of illuminating the satellite, only three are considered. In order of merit these are

1) a pulsed searchlight illuminator coupled with an optical corner reflector;
2) sunlight illumination; and
3) pulsed light on the satellite.

For purposes of the gravitation experiments under consideration, it is necessary to be able to observe the satellite for a long period of time, *i.e.*, in excess of a year. Consequently, it appears that only solar battery operation should be considered. This requirement makes the pulsed light [3) above] a not very favorable approach.

With searchlight illumination of an optical corner reflector with a 10-cm edge it is easy to make a satellite at 2000 km appear brighter than a 6-magnitude star. This is far more light than can be obtained with sunlight illumination of a satellite of the same size. With all this light available, the searchlight may be pulsed and the satellite photographed against a fixed star field, the image of the satellite appearing as a trail of dots in the star field.

At higher elevations it is necessary to consider sunlight illumination and photoelectric tracking of a satellite. For purposes of photoelectric detection of a satellite illuminated by the sun, there are decided advantages, in connection with problems of acquisition and tracking, in having a modulated light source. To this end the satellite is given an "orange peel" structure by being covered by curved reflecting strips. As the satellite rotates these metallic strips reflect the sunlight in well defined fans of illumination which sweep over the observer. The satellite scintillates periodically.

Photoelectric tracking of a 10-cm radius satellite using these orange peel reflectors of sunlight appears possible for satellites as high as 50,000 km with a 20-inch telescope. Furthermore, for a satellite this size the intensity of light in each scintillation is adequate for photographing the satellite directly without tracking as a series of dots against a fixed star field up to an elevation of 10,000 km with a 20-inch telescope and 50,000 km with a 60-inch telescope.

Thus it appears that for low altitude satellites the pulsed searchlight and corner reflector method is superior while at higher altitudes reflected sunlight observed either by direct photography or by photoelectric tracking is more suitable.

Comparison of Optical Methods for Observing Satellites

We shall discuss three methods for optically observing a satellite:

1) searchlight illuminating a corner reflector;
2) sunlight illuminating a sphere; and
3) flashing light on the satellite.

The satellite to be observed is at a height of either 2000 km (if only neutral drag is important), or 50,000 km (if electrical drag is important and it is necessary to go above the Van Allen layers). At 2000 km above the earth's surface, the density of the earth's atmosphere should be equal to that of interplanetary gas.

Table I summarizes some of the orbital and size parameters of interest for satellites at heights of 2000 km, 50,000 km and at an intermediate height of 10,000 km.

TABLE I

Satellite Parameters

Height (km)	2000	10,000	50,000
Period (hour)	2.2	5.8	37.4
Apparent angular[1] velocity (seconds of arc per second of time)	700	100	11
Linear velocity (Km per second)	6.9	4.9	2.7
Revolutions per year	4100	1,500	240
Mass (kg)	10	10	10
Linear dimensions (cm)	10	10	10

[1] Angular velocity as observed from the surface of the earth when the satellite is near the zenith.

The mass of 10 kg is chosen so that launching will not be unusually difficult; a linear dimension of 10 cm corresponds to an average density (for a sphere of radius 10 cm) of 2.5 gm/cm^3. If possible it would be better to use a larger mass to decrease the ratio of drag to inertia.

No matter which of the above methods is used, it is necessary to have a preliminary orbit so that the position of the satellite can be predicted (to within about a degree). Such an orbit can be obtained from a radio transmitter either in the satellite itself, or from a second companion satellite launched from the same rocket and remaining near the first one during the early days of its life.

Optical tracking of a satellite can give satellite positions good to $\sim 1/10$ second of arc at times known to 10^{-3} seconds over a year. In the case of the satellite at 2000 km, it would then take 1 year to detect a change in the gravitational constant, G, of a part in 10^{10} per year. For a satellite at 50,000 km, which makes fewer revolutions per year, the time required would be longer (approximately 4 years).

Low Altitude Satellite (2000 km)

We first compare methods 1) and 2) of those mentioned above. Consider a satellite illuminated by the sun or by a searchlight which is 2000 km away and

200 cm in diameter. Such a searchlight subtends an angle 0.2 seconds of arc at the satellite, or a solid angle 10^{-8} times smaller than that subtended by the sun. If the searchlight were as bright as the sun, the light falling on the satellite from it would then be weaker than the light from the sun by a factor 10^{-8}.

However, a satellite illuminated by a searchlight can be made a corner reflector, which reradiates the light incident on it into a small, diffraction-limited solid angle, while a polished sphere reflecting sunlight scatters the light incident on it into a solid angle 4π. This favors the searchlight illuminated corner reflector by a factor $4\pi(l/\lambda)^2$, where l is the linear dimension of the corner reflector and λ the wavelength of the incident light. For $l=10$ cm and $\lambda=5\times10^{-5}$ cm, this factor is approximately 5×10^{11}. Hence in comparing two satellites of the same size, one a sphere reflecting sunlight, the other a corner reflector illuminated by a searchlight, the latter reflects more light to a telescope on the ground by a factor of 5000.

The suggested method for photographing the corner reflector satellite is to pulse the searchlight with a 5 per cent duty cycle so the satellite track appears as a series of dots against the star field. The same method may be applied to observation of a sphere reflecting sunlight if the spherical surface is modified to an orange peel configuration formed by a series of curved cylindrical reflecting strips on the satellite surface which produce a series of pulses as the satellite rotates. Comparing these two methods for satellites of the same size at 2000 km, the amount of light received per exposure from the corner reflector is 16 times that from the modified sphere, providing total exposure times are the same.

We now compare methods 2) and 3) of those mentioned above. Since the satellite considered will have to be observed for at least a year, a flashing light must be powered by solar batteries, which have efficiencies of approximately 5 per cent. In effect, one may think of the solar batteries as collecting 5 per cent of the light falling on the satellites in one revolution around the earth and then reradiating a fraction of it on demand. This fraction is determined by the luminous efficiency of the pulsed lamps, which for a low pressure noble gas discharge of the type used by photographers is about 5 per cent. Assuming the satellite to be a sphere whose surface is covered by batteries, the same amount of light would reach a telescope on the ground from a polished sphere (of the same radius) reflecting sunlight while it traveled over an arc equal to 0.25 per cent of 360° or 1° viewed from the center of the earth or 4° viewed from the surface. (This assumes that the satellite is never in the earth's shadow.) On the other hand, a sphere reflecting sunlight may be observed while traveling an arc of 30° viewed from the surface. Thus, considerably less light is available for each observation from a solar battery powered flashing light on a satellite than from a sphere reflecting sunlight.

We may conclude that a searchlight illuminated corner reflector gives the most light of the three methods mentioned above for viewing a satellite 2000 km away. The more detailed discussion of this method in the following section shows that $\sim10^7$ photons/second can be expected to arrive at a telescope of diameter 20 inches. This is enough that a telescope viewing the satellite need track only the stars; the satellite can be photographed directly as a sequence of dots against a background of fixed stars.

An interesting advantage of the searchlight method is that, because of aberration, the reflected beam returns to the earth about 100 meters from the searchlight; to view the satellite we need only bring a searchlight close to an existing astronomical telescope.

A further advantage of the searchlight over sunlight illuminated satellites is that the searchlight-illuminated satellite's position can be measured any night when the sky is clear and the satellite is not too far from the zenith, whereas observation of the sunlight illuminated satellite depends on the correct relative position of the sun and the satellite. It is also easier to make accurate time measurements with a regularly flashing bright searchlight than with a sequence of fainter flashes coming from a sunlit orange peel sphere.

It should be remarked, however, that the technique of sunlight illumination of an orange peel structure has much to recommend it in terms of its simplicity.

High Altitude Satellite (*50,000 km*)

For a 10-cm satellite 50,000 km above the surface of the earth, none of the three methods give enough light at a 20-inch telescope to photograph the satellite directly while tracking the stars. The telescope must be made to follow the satellite while enough light is collected to photograph it; to stop the apparent motion of the background reference stars while these are being photographed, a rotating glass plate can be used as in the Markowitz moon camera.

Since the highest angular velocity to be compensated for is 15 seconds of arc per second of time, no difficult mechanical tracking problems arise. (The situation might be otherwise if the telescope were tracking a satellite at 2000 km, since such a satellite has a high apparent angular velocity—12 minutes of arc per second of time.)

At an altitude of 50,000 km, searchlight illumination of a corner reflector does not give more light at the telescope than sunlight reflected from a sphere of the same size; this is because the amount of light reflected from a corner reflector to the ground is proportional to l^4/h^4 ($l=$linear dimensions of corner reflector, $h=$height above ground), while the amount of sunlight scattered from a sphere to the ground is proportional to l^2/h^2 and so decreases more slowly with increasing height. At 25,000 km a polished sphere of radius 10-cm and a continuously illuminated corner reflector of edge 10-cm

reflect the same amount of light to the ground (350 photons per sec in a 20-inch telescope). At an altitude of 50,000 km, a sunlit sphere of radius 10-cm gives $\sim$100 photons per sec at the ground, while a searchlight illuminated corner reflector (10-cm edge) gives $\frac{1}{3}$ this amount.

Thus for a high altitude satellite, searchlight illumination has the disadvantage of less light than the other two methods. The sphere gives as much light as the flashing light and is considerably simpler. Furthermore, the modified 10-cm sphere viewed by a 60-inch telescope provides enough light to permit direct photography without satellite tracking. Hence, it appears that at 50,000 km the modified orange peel satellite reflecting sunlight is most suitable.

Summary

Table II summarizes the data on the amount of light collected by a telescope of aperture 20 inches from a 10-cm satellite.

TABLE II

LIGHT COLLECTED BY A 20-INCH TELESCOPE FROM A 10-CM SATELLITE

Height (km)	Corner Reflector[1] Photons per Second	Sphere[2] Photons per Second	Flashing Light Powered by Solar Batteries[3] Photons
2,000	1.3×10^7	6.8×10^4	1.3×10^6
10,000	2×10^4	2.7×10^3	1.4×10^5
50,000	33	108	3.6×10^4

[1] Searchlight continuously operated at peak intensity.
[2] Average intensity.
[3] Obtained by multiplying the average intensity from the sphere by the time required for the satellite to go 0.25 per cent of a revolution.

These photon currents will then be used to expose a photographic plate. In all photographic discussions we assume that 1000 photons are required for each developed grain. The number of grains available in one "picture" of the satellite (used to obtain one measurement of position and time) are then as shown in Table III taking a 10-cm satellite and 20-inch telescope.

TABLE III

NUMBER OF PHOTOGRAPHIC GRAINS IN A SATELLITE OBSERVATION WITH A 10-CM SATELLITE AND A 20-INCH TELESCOPE

Height (km)	Corner Reflector[1]	Sphere[2]	Sphere[3]	Flashing Light[4]
2,000	50,000	5000	3000	1300
10,000	550	1400	900	140
50,000	7	380	300	36

[1] Number of grains formed in 15 exposures made while the satellite is within 30° of the zenith, each exposure taking the time for the satellite to cross 1° in the sky. The duty cycle of the searchlight is taken to be 5 per cent.
[2] Number of grains formed in a single exposure with a telescope tracking the satellite while it crosses 30° near the zenith.
[3] Number of grains formed in 15 exposures made while the satellite is within 30° of the zenith by the method of direct photography of pulses from a modified spherical satellite. Each exposure lasts while the satellite traverses 1° in the sky.
[4] Computed from Table II assuming 1000 photons required to give 1 developable grain.

CORNER REFLECTOR ILLUMINATED BY SEARCHLIGHT

In this section, we shall discuss in detail the observation of a satellite corner reflector illuminated by a searchlight beam.[4]

The Searchlight

High pressure mercury arcs are now available which are approximately as bright as the sun

$$2 \times 10^{10} \frac{\text{ergs}}{\text{sec cm}^2 \text{ steradian}} = 8 \times 10^{20} \frac{\text{photons}}{\text{sec cm}^2 \text{ steradian}}$$

(taking one erg of solar radiation to give 4×10^{10} visible photons). If such an arc were installed at the focus of a parabolic mirror whose radius was 100 cm, a beam of intensity

$$\pi \times 10^4 \times 2 \times 10^{10} = 6.3 \times 10^{14} \frac{\text{ergs}}{\text{sec steradian}}$$

$$= 2.5 \times 10^{25} \frac{\text{photons}}{\text{sec steradian}}$$

would be directed toward the satellite. Such an arc can either be operated continuously or modulated up to 10^4 cps.

The mirror must be good enough that its focus just covers the arc. It may be desirable to use a small, precision optical system to collect light from a large solid angle around the arc and act as a bigger source sending out light into a smaller solid angle to a long focus parabolic mirror. Since radio tracking will give a preliminary orbit to about 1°, the divergence of the searchlight beam should at least initially also be about 1°, which corresponds to a power of 20 kw if the searchlight is operated continuously.

The Corner Reflector (2000 km)

The corner reflector reradiates the incident searchlight beam into a small solid angle determined by the reflector's linear dimensions. For a satellite 2000 km away and having linear dimensions 10 cm, the intensity of the reflected light would be that of the incident light, multiplied by the factor

$$\left(\frac{10}{2 \times 10^8}\right)^2\left(\frac{10}{5 \times 10^{-5}}\right)^2 = 10^{-4}$$

which gives a beam of intensity

$$6.3 \times 10^{14} \times 10^{-4} = 6.3 \times 10^{10} \frac{\text{ergs}}{\text{sec steradian}}$$

$$= 2.5 \times 10^{21} \frac{\text{photons}}{\text{sec steradian}}.$$

[4] Illumination of a satellite in the form of a corner reflector by a searchlight has been studied by others. In particular the work of the Army Map Service is reported by J. O'Keefe, "The geodetic significance of an artificial satellite," which appears as Appendix E in "On the utility of an artificial unmanned earth satellite, a proposal to the national science foundation prepared by the American Rocket Society Space Flight Committee Nov. 24, 1954," *Jet Propulsion*, vol. 25, pp. 75–76, February, 1955.

This is true, however, only in order of magnitude because the effective cross section of the corner reflector will depend on its orientation.

In particular, consider a corner reflector made up of isosceles triangles, as shown below, and let the effective cross section be fl^2, where l is the length of one edge CV (from the corner to a vertex). By the effective cross section, we mean that if one photon per cm^2 were incident on the reflector, fl^2 photons would be reflected.

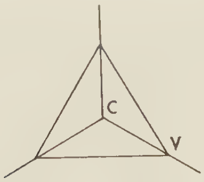

Fig. 1.

The maximum value of f occurs when light strikes the reflector along its axis of symmetry and is $1/\sqrt{3} = 0.58$, while the minimum value is zero. Numerical calculations show that if all directions in the one octant covered by the reflector were equally probable, then f would be distributed approximately uniformly in the interval (0, 0.58).

However, the amount of light reaching the telescope from the reflector depends also on the solid angle into which the reflector sends its light. Assuming that the diffraction width is given by the square root of the effective cross section (*i.e.*, by the length $\sqrt{f}\,l$), then the light reaching a telescope on the ground becomes proportional to f^2; f^2 is not uniformly distributed in the interval to (0, 1/3), small values being more likely than large ones. Its mean value is 1/9.

If the satellite were made of 8 corner reflectors (each having an edge 10 cm) packed into a cube, the effect of random orientations would be to multiply the light reaching the telescope by approximately 1/10.

Another possibility is to use only one corner reflector, and to set it spinning about a principal axis perpendicular to its axis of symmetry, the axis of revolution being oriented with respect to the satellite's orbit in such a way that the symmetry axis of the reflector is always in the plane of the orbit. If the satellite is near the zenith, the mean value of f^2 turns out to be between 10^{-2} and 10^{-1}, so the amount of light reaching the telescope in this case would be somewhat less than for eight corner reflectors packed into a cube.

The conditions to be met in construction of the corner reflector are that the plates be flat to less than a 1/4 wavelength and mutually perpendicular to a second of arc. These conditions are necessary in order that the solid angle into which the corner reflector radiates be determined by its diffraction width. To assemble such a reflector in the laboratory presents no unusually difficult problems; to preserve the alignment during the launching should not be too difficult.

The weight of the corner reflector is determined by how heavy an object can be put into orbit, and should be as large as possible to minimize the effect of gas drag.

Observations of a 2000-km Satellite

Taking the average value of f^2 as defined in the preceding section to be 1/10, the reflector will give

$$\frac{6.3 \times 10^{10} \times 10^{-1}}{(2 \times 10^{8})^2} = 1.6 \times 10^{7} \frac{\text{ergs}}{\text{sec cm}^2}$$

$$= 6400 \frac{\text{photons}}{\text{cm}^2 \text{ sec}}$$

at the surface of the earth, which corresponds to a star of magnitude +5.5 (barely visible to the naked eye). A 20-inch telescope (area 2000 cm^2) will collect 1.3×10^7 photons per second at its focus.

The light-time from the searchlight to the satellite and back is 13×10^{-3} seconds, in which time the earth's surface, because of the satellite's motion, moves $13 \times 10^{-3} \times 7 \times 10^3 \approx 100$ meters relative to the satellite. Hence the telescope used for observing the satellite should be displaced 100 meters from the searchlight so that no problems about transmitting and receiving with the same instrument arise.

The photon current at the telescope focus is so large that in the time (1.4×10^{-3} seconds) required for the satellite to go 1 second of arc, 1.8×10^4 photons have struck a photographic plate at the focus. This will give 18 developable grains in the satellite image (assuming that 1000 visible photons are required to produce 1 developable grain). By matching the emulsion response to the searchlight spectrum, it may be possible to increase further the number of developable grains per satellite image.

To photograph such a satellite at 2000 km, then, it is possible to use an existing astronomical telescope to track the stars while the satellite crosses the telescope's field of view. A pulsed searchlight on for 1.4×10^{-3} seconds and off for a time $19 \times 1.4 \times 10^{-3} = 27 \times 10^{-3}$ seconds would record the satellite as a string of dots 1 second of arc long and 20 seconds of arc apart, each dot containing about 18 developable grains. If the field of view of the telescope were $1° \times 1°$, the satellite would take 5.2 seconds to cross it and leave 180 dots containing a total of 3300 grains. Since each dot determines the satellite position to about 1 second of arc, the trail of dots can determine its position at a well-known time to better than 1/10 second of arc (omitting systematic errors).

A photoelectric cell monitoring the searchlight and coupled to a crystal clock could record the time of each dot to 10^{-4} seconds, the omission of every tenth pulse providing fiducial marks. Then each such 5-second exposure would, in effect, determine the position of the satellite to 1/10 second of arc at a time known to 10^{-4}

seconds, which is adequate to look for a change in G of a part of 10^{10} per year.

In the preceding, the duty cycle (5 per cent) of the searchlight is chosen so that the searchlight is off when the light pulse reflected from the satellite comes back to the telescope. A synchronized shutter at the telescope could be used to shield the film while the searchlight was on, the duty cycle of the shutter being adjustable so that the exposure given the background stars could be varied from 5 seconds to 1/4 second.

The effective focal length of the telescope must be such that the seeing disc of the satellite ($\sim$1 second of arc) covers roughly 18 grains. Taking a grain to be 10^{-4}-cm long, the scale of the image on the photographic plate becomes roughly 4 microns per second of arc corresponding to an effective focal length 80 cm. With such a scale, a $1° \times 1°$ field of view fits on a piece of emulsion 1 cm$\times$1 cm.

Since the telescope follows the stars and not the satellite, the tracking problem for it is not difficult. On the other hand, though the satellite moves rapidly (12 minutes of arc per second of time) across the sky, the searchlight beam is so wide ($\sim$1°) and the satellite so bright that no serious difficulties either in finding it or following it arise.

Distant Satellite

The method described above can be used only when there is enough light coming from the corner reflector that about 1000 photons arrive in the time it takes the satellite to move 1 second of arc. At heights above 5000 km, this is no longer true for a 10-cm corner reflector and a 20-inch telescope; the telescope must then be made to track the satellite.

Direct photography at higher altitudes is possible only with a larger telescope or corner reflector. At 50,000 km, a 10-cm corner reflector gives only 33 photons per second at the focus of a 20-inch telescope. When applied to such a satellite, the method described above gives only 3 photons per dot. However, increasing the telescope aperture to 60 inches and making the edge of the corner reflector 30 cm instead of 10 cm would increase the photon current by a factor $3^6 \approx 750$, which would make direct photography practicable, there being 2 grains per dot. However, the orange peel construction for a sphere at 50,000 km permits direct photography using reflected sunlight to give 20 grains per dot with a 60-inch telescope. Thus this latter construction is preferable at high altitudes.

Satellite Illuminated by Sunlight

This section is a description of the observation by reflected sunlight of a modified spherical orange peel satellite.

Illumination

The weak intensity of reflected sunlight from a small satellite necessitates special light modulation techniques for direct photography or, for more distant satellites, photoelectric detection for finding the satellite and precision tracking to permit long time exposure photography.

The sunlight reflected from a polished sphere to an observer on the earth is

$$W_1 = \frac{W_s}{4\pi} \pi R^2 \left(\frac{\pi a^2}{4h^2} \cos^2 \psi \right)$$

where ψ is the angle of the satellite from the zenith. Using the values for the radius of the satellite $R=10$ cm, aperture of the telescope $a=20$ inches, height of satellite $h=2000$ km, intensity of sunlight at the surface of the atmosphere, $W_s=1.37\times10^6$ ergs/cm^2-sec from Table I and the Appendix and taking $\psi=0$ for overhead viewing,

$$W_1 = 1.7 \times 10^{-6} \text{ ergs/sec.}$$

This power represents 6.8×10^4 photons per second in the visible spectrum and is equivalent to a star of the 11$^{\text{th}}$ magnitude.

The angular size of the image of the satellite at the focus of the telescope is determined by atmospheric turbulence which produces an image of about 1 second of arc diameter. The background light entering the telescope in a second of arc, using W_B given in the Appendix, is

$$W' = W_B \frac{\pi a^2}{4} \frac{\pi}{4} \Omega^2 = 1.16 \times 10^{-10} \text{ ergs/sec}$$

which is 7.1×10^{-5} times the signal power and will permit distinguishing the signal from the background.

From Table I a satellite at an elevation of 2000 km has an apparent angular velocity at the zenith of 700 seconds of arc per second of time. Photographing the position to an accuracy of 1 second of arc with a fixed telescope would require an exposure of 1.4 msec yielding only 95 photons for the 10-cm satellite, not nearly the 1000 required to produce a developed grain. Thus the polished sphere reflecting sunlight does not lend itself to direct photography against a background of fixed stars.

In the next paragraph, a nonspherical satellite is discussed which modulates the reflected light into high intensity pulses which for the nearby satellites is adequate for direct photography. However, the light intensity at a 20-inch telescope from a more distant 10-cm satellite is still too weak for this method and precision tracking is necessary for long time exposures. For such tracking a nonspherical satellite is also desirable for simplifying identification and improving signal-to-noise.

The Orange Peel Construction

Identification is simplified, signal-to-noise improved, and direct photography without satellite tracking as discussed above made possible by constructing the satellite of cylindrical sectors bounded by planes radiating from the axis, forming an orange peel configuration as shown in Fig. 2. As the satellite rotates, the light at an

observer is modulated into pulses of intensity,

$$W_2 = W_1 \frac{4 \sin \theta \cos \frac{\phi}{2} \tan \frac{\pi}{n}}{\alpha},$$

where ϕ is the angle at the satellite between the sun and the telescope, projected onto that meridian plane of the satellite which passes through the point of reflection; θ is the angle from the axis of the satellite to the radius which bisects ϕ; α is the angular width of the sun; and n is the number of sectors. The light from this modified sphere is reflected into fan-shaped wedges whose angular width is approximately 1/2°, the angle (α) subtended by the sun. Since we observe at night,

$$\phi < \frac{\pi}{2} \quad \text{so that} \quad \cos \frac{\phi}{2} > 0.7.$$

For the axis of the satellite along the earth's polar axis

$$\frac{\pi}{2} - \theta < 45° \quad \text{and} \quad \sin \theta > 0.7.$$

So the intensity of the pulse is

$$W_2 \geq \frac{2W_1}{\alpha} \tan \left(\frac{\pi}{n}\right).$$

The average intensity is W_2 times the ratio of the angular width $\alpha/2$ to the angular width of one segment $\alpha n/4\pi$. For π/n small so $\tan (\pi/n) \simeq (\pi/n)$

$$\overline{W}_2 = \frac{1}{2} W_1.$$

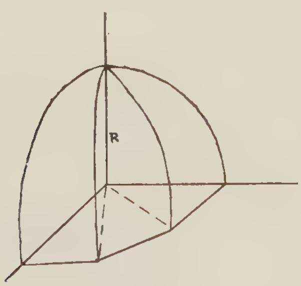

Fig. 2.

Direct Photography

With the orange peel satellite discussed in the previous section, it is possible to photograph the satellite as a series of dots on a photographic plate on a standard observatory telescope set to track the star field. The exposure time of the dots is determined by the reflected light pulse length.

In order that the 1-second "seeing" image of the satellite produced by atmospheric turbulence not be further blurred by the satellite's apparent motion of 700 seconds of arc per second of time for a 2000-km satellite, it is necessary that the pulse length produced by the rotating orange peel be less than 1.4 msec. Thus, it is necessary that the satellite rotate at least 1/4° in 1.4-msec or 1/2-revolution per second so that the 1/2° width of the fan-shaped wedge of reflected light will sweep completely across the telescope in 1.4-msec. Choosing the number of segments to be 4, the intensity of the pulse

$$W_2 = \frac{2W_1}{\alpha} \tan \frac{\pi}{n} = 220\, W_1.$$

The number of photons per pulse for a 10-cm radius satellite and 20-inch telescope is 20,000 and hence the number of grains per pulse exposed in the photographic plate is 20. The number of dots occurring at 2 per second in the 5 seconds the satellite takes to pass over a 1° field of view is 10 yielding a total of 200 grains per exposure.

This is an adequate number of grains to locate the satellite to 10 per cent of its image diameter. However, the anticipated number of grains from a corner reflector of the same size and height reflecting light from a pulsed searchlight for the same 5-second exposure is sixteen times larger. In addition, the orange peel satellite is not observable when it is in the shadow of the earth. Therefore, the searchlight and corner reflector appears to be a more suitable method for observing a 2000-km satellite by direct photography.

At 10,000 km the length of the pulse and the total length of the exposure can be increased by a factor of 7 because of the smaller apparent motion of the satellite (Table I), while the intensity is reduced by a factor of 25 because of the increased distance. The resulting minimum rotation is 1/14-revolution per second and exposure time 35-seconds. The number of photons per dot is approximately 0.3 times the number at 2000 km yielding only 6 grains per dot and a total of 60 grains per exposure for the same 10-cm radius satellite and telescope. A greater rate of rotation will decrease the number of grains per dot while increasing the number of dots per exposure so the total number of grains per 35-second exposure remains constant (as long as a sufficient number of grains occur in each dot to be discernible). At this elevation direct photography of the orange peel satellite produces twice as many grains as a 10-cm corner reflector and pulsed searchlight for the same 35-second exposure. Six grains per dot is marginal, but should produce a discernible and measurable track.

At 50,000 km, the length of the pulse and the total length of the exposure can be increased by a factor of 9 over the values at 10,000 km because of the reduced apparent motion of the satellite (Table I), while the intensity is reduced by another factor of 25. The resulting rotation rate is 1/126-revolution per second and exposure time is 315 seconds. The number of grains per dot for a satellite and telescope of the same size is down to 2 and per exposure 20 which is inadequate for

reliable determination of the satellite position. By going to a larger telescope (60-inches) these numbers are increased by a factor of 10 and the method remains feasible.

Photoelectric Detection and Tracking

The position of a distant satellite can be recorded by photographing with a long time exposure simultaneously on the same photographic plate the satellite and the star field stopping their relative motion by the method of a rotating glass plate as used in Markowitz' moon camera. Since the satellite is weaker than the stars to be photographed, it is desirable to track and continuously photograph the satellite while exposing successively different star fields for a few seconds while their motion is stopped by the rotating plate.

Tracking is accomplished by splitting the light in the telescope by a beam splitter, focusing one beam at the photographic plate and the other onto a diaphragm behind the opening of which is a pyramid which partitions the image of the star among four photomultipliers. The signals from the photomultipliers are amplified in a narrow-band amplifier tuned to the modulation frequency of the light, and intercompared to determine the position of the satellite image relative to the pyramid vertex.

It is assumed that radio tracking of this or of a companion satellite gives the position of the satellite fairly accurately so that finding the object with the optical system is not a problem. This requirement will be shown to be 1° for radio tracking accuracy for the 2000-km, 10-inch radius satellite and 20-inch telescope, 10 minutes for the same object at 10,000 and 1 minute at 50,000-km. The diaphragm opening need only be made large enough so that when the telescope is positioned according to radio tracking, the image of the satellite will with certainty drift across the diaphragm opening. The presence of the ac signal will then initiate the tracking motion in order to keep the image on the vertex of the pyramid to 10 per cent of the image size (0.1 second of arc.)

This requirement of tracking accuracy puts a minimum on the acceptable signal intensity times the averaging time of the tracking control loop, since for 10 per cent positioning accuracy the photomultiplier cathode must produce at least 100 photoelectrons during the averaging time. For a photocathode with a frequency response three times the visual response and with an efficiency of 10 per cent, we need an energy of 8.3×10^{-9} ergs. If we include a factor of two for energy lost by the beamsplitter and another factor of two for the pyramid, the minimum average intensity of satellite light falling on the 20-inch telescope for an averaging time of 1 second is

$$3.3 \times 10^{-8} \text{ ergs/sec}$$

which is equivalent to a star of magnitude 15.5. This is 1/50 as bright as the 2000-km, 10-cm satellite and 12 times as bright as the 50,000-km satellite of the same size. Thus, in the former case, we may reduce the averaging time to 0.1 or 0.05 seconds and in the latter case we must increase it to 10 or 20 seconds.

The condition of finding puts a second limit on the dimness of a detectable object. It is necessary that we be able to distinguish the satellite from background during the time interval that the image of the satellite is crossing the diaphragm opening. The photoelectron noise fluctuations caused by the background skylight during the time for a 2000-km satellite to cross a 1° diaphragm opening is the number of photoelectrons produced by a signal of

$$2.1 \times 10^{-7} \text{ ergs/sec}$$

for a 20-inch telescope, which is 1/8 of the signal available from a 10-cm satellite at 2000 km. The noise signal is proportional to the square root of the diaphragm opening and the square root of the apparent angular velocity. For satellite and telescope of the same size at 10,000 km, the noise for the 10-minute opening is 1/2 the available signal and at 50,000 km it is equal to the available signal for a 1-minute opening.

During tracking it is necessary that the noise fluctuations be less than 10 per cent of the signal during the averaging time. For an averaging time of 1 second and an opening of 10 minutes the signal required for a 20-inch telescope is

$$8 \times 10^{-7} \text{ ergs/sec}$$

which is 1/2 the signal available for the 10-cm 2000-km satellite. The signal required is proportional to the opening and inversely proportional to the square root of the averaging time. At 10,000 km, for a 1-minute tracking diaphragm the signal required is equal to the signal available from the 10-cm radius satellite and at 50,000 km, for a 10-inch tracking diaphragm and 10-second averaging time the signal required is 4×10^{-9} ergs per second, which is slightly larger than the signal available. Thus it appears necessary, at least for the higher altitudes, to use a separate and smaller diaphragm for tracking than for finding.

A fourth limitation on the brightness of object observable is the mechanical noise in the telescope drive mechanism. Assuming a one second averaging time for the 2000-km satellite the requirement of freedom from tracking noise to 0.1 second of arc means that mechanical noise must be less than 0.1 inch per second or less than 0.014 per cent of the tracking velocity. At 10,000 km, this is 0.08 per cent of the tracking velocity. At 50,000 km, the telescope motion is largely caused by the rotation of the earth of 15 inches per second and the problems are no different from those of tracking the star field.

Because of this demand for precision, it is worth considerable effort to obtain a good mechanical system. Lapped conical bearings with a clearance of 10^{-4} inches at the ends of a 20-inch yoke permit an angular play of less than 1 second of arc. The drive mechanism might be a lapped screw driven by a servo-controlled motor with electromagnetic application of torque for relatively fast feedback. It may be desirable to employ an auxiliary feedback loop over a mechanical-electrical rate indicator to reduce mechanical noise. The rate indicator could employ the electromotive force induced in a coil rotating with the telescope to sense the telescope rotation rate.

Photographing Satellite and Stars

With the telescope tracking a rapidly-moving low satellite, the problem of simultaneously photographing the star field is a considerable one. If we stop the motion by a short exposure of 1.4 msec., a star magnitude of 3 is required to produce about 100 developed grains on the photographic plate for a 20-inch telescope. But there are only 0.0025 stars per square degree of magnitude this bright. Hence it is necessary to remove the apparent angular motion of the star field. If this is done to 2 per cent accuracy so that the apparent star motion is approximately the sidereal rate, the exposure length can be 67 msec permitting exposures of stars to 7.5^{th} magnitude which average about 0.3 per square degree. Finally, if we remove the telescope motion to 0.1 per cent and introduce a sidereal correction into the rotating mirror accurate to 10 per cent, we gain by a factor of 10 permitting 1/2-second exposures of stars to 10^{th} magnitude. With 4 of these per square degree there should be no trouble finding an adequate number of reference stars.

This problem decreases rapidly with increasing height of the satellite. At 10,000 km, the apparent angular motion is 100 seconds of arc per second of time. With the relative motion of star field removed by the rotating plate to 0.1 per cent and a 1 per cent accurate correction for sidereal motion, stars down to 12^{th} magnitude can be photographed with 5-second exposure time. With 25 of these per square degree, there is no difficulty in photographing an adequate star field for 10,000 km or any more distant satellite.

The satellite is to be observed and photographed with a 20-inch telescope while within about 30° of the zenith. In the 2 1/2 minutes the 2000-km satellite takes for an apparent motion of 30° near the zenith, the image of the satellite on the photographic plate receives 1.3×10^{-4} ergs or 5×10^{6} photons. This results in 5000 developed grains which is more than adequate for locating the image to 0.1 of the seeing disk.

At 10,000 km, the exposure time is increased by a factor of 7 while the satellite brightness decreases by a factor of 25 so the image contains 1400 developed grains. At 50,000 km, the exposure time is limited by the earth's rotation to two hours, yielding 380 developed grains which is still an adequate image.

Thus, we conclude that for satellite heights of 2000 km and perhaps 10,000 km, we may directly photograph a moving orange peel satellite of 10-cm radius as a series of dots against the background star field with a 20-inch telescope. At the lower elevation the signal is less than that from a corner reflector. At the higher elevation it is about the same. At 50,000 km, we may use this method with the 10-cm radius orange peel satellite if we observe with a 60-inch telescope.

The method of tracking the satellite with the telescope produces adequate signal for all three distances considered. However, at 2000 km mechanical problems caused by rapid apparent satellite motion makes this method unsuitable. At the higher elevations the mechanical problems become no greater than those of sidereal tracking of stars. The basic limitation is the signal-to-noise caused by the small number of photons per second from the satellite. This limitation restricts this method to about 50,000 km for a 10-cm radius satellite and 20-inch telescope.

It should be noted in comparing the sunlight with the searchlight methods that the former depends for observation upon the relative orientation of the sun, satellite and observer. During two seasons of the year the satellite in a polar orbit is in the earth's shadow half the time permitting observation at night near the zenith only for an observer at about 45° North (or South) latitude utilizing the sun's rays coming over the pole.

Conclusion

Of the various possible ways of illuminating a satellite at heights of 2000–50,000 km, only two have been found to be promising for gravitation experiments requiring very precise position observations over long observation periods. The pulsed searchlight used on a satellite in the form of a corner reflector is particularly suitable at heights under 5000 km. At all heights in the range 2000–50,000 km, sunlight illumination of an orange-peel satellite is effective. The satellite rotates about the axis of the "orange" and scintillates brilliantly as sunlight is reflected from curved strips. At 50,000 km the orange peel satellite is tracked photoelectrically, the modulated light giving the satellite signal a distinctive character which separates it from background "noise." At lower altitudes the scintillating satellite may be photographed directly. For this purpose it should have but 3–4 strips in the form of cylindrical surfaces and should rotate about the axis of the orange sufficiently rapidly that the satellite effectively stands still during any single flash, but slowly enough that the total number of photons per flash is a maximum subject to the first condition.

To photograph satellites at an altitude of 2000 km, the pulsed searchlight gives much more light than the orange-peel satellite. It also has the advantage of making the satellite visible during the night when the satellite is in the earth's shadow. Another advantage is that accurate time measurements are easily carried out. The chief advantage of the orange-peel at low altitudes is one of simplicity.

At high altitudes the pulsed searchlight technique is not feasible, while direct photography without tracking of the orange-peel satellite may be undertaken with a larger (60-inch) telescope.

Appendix

The following table summarizes the astrophysical and photometric constants used in the preceding discussion. The numbers were taken from Allen[5] and from McGee.[6]

Constants Used in the Preceding Discussion

Intensity of sunlight at the surface of the atmosphere,

$$W_s = 1.37 \times 10^6 \frac{\text{ergs}}{\text{cm}^2 \text{ sec}}.$$

[5] C. W. Allen, "Astrophysical Quantities," Athlone Press, London, Eng.; 1955.

[6] J. D. McGee, "Photoelectric Aids in Astronomy," in "Astronomical Optics and Related Subjects," North Holland Publishing Co., Amsterdam, Holl., pp. 205–223; 1956.

Light from the background sky (total brightness near the zenith),

$$W_B = 7.5 \times 10^{-14} \frac{\text{ergs}}{\text{sec cm}^2 \text{ (sec of arc)}^2}.$$

Brightness of the sun,

$$B = 2 \times 10^{10} \frac{\text{ergs}}{\text{cm}^2 \text{ sec steradian}}.$$

Star magnitudes: a magnitude zero star gives

$$2.5 \times 10^{-5} \frac{\text{ergs}}{\text{sec cm}^2} \text{ outside the atmosphere;}$$

or 4.9×10^{-2} ergs per second at focus of telescope whose diameter is 20 inches.

Luminous efficiency of sunlight,

$$100 \frac{\text{lumens}}{\text{watt}}.$$

1 lumen corresponds to 4×10^{15} visible photons (calculated assuming 685 lumens per watt at 5550 A).

1 erg of radiation from a block body at 5800°C gives 4×10^{10} visible photons.

Photographic efficiency,

1 grain per 1000 visible photons.

Photoelectric efficiency,

0.3 photoelectron per visible photon.

Field Emission, A Newly Practical Electron Source*

W. P. DYKE†

Summary—**The properties of the field emission electron source are discussed. These include high current density, small size, no heater, instantaneous response, and a highly non-linear current-voltage relationship. Engineering data are then derived including conductance, perveance, beam power, etc. It is shown that the field emission cathode is electrically stable and that it has long life given suitable environments and/or operating conditions which are specified. Microwave, voltage control and measurement, electron optical and other applications are discussed. A 300-megw flash X-ray tube now in production is described. The availability of the field emitter as a newly practical electron source is expected to make possible a number of new devices which may more often complement than compete with existing technology.**

RECENTLY[1] a microscopic cold tungsten needle yielded a stable electron beam power of 35 watts average in a sealed off vacuum diode for 1000 hours of unattended dc operation (see Fig. 1). This experiment teaches that the smooth, clean field emitter is electrically stable; other experiments indicate that it may have indefinite life. The practical value lies in the unusual properties of this cathode which may affect the design of advanced electronic systems. The cathode current density during the experiment mentioned above was 10^7 amperes /cm^2, a level heretofore reached only during pulsed operation, and about a million times larger than that commonly attained from conventional cathodes. Increased current density can provide higher frequency, better resolution, greater efficiency and smaller size in certain electron devices.

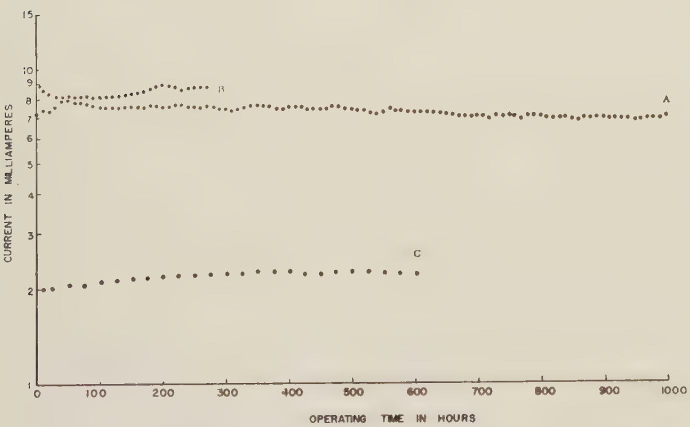

Fig. 1—Graph showing the emitted field current *vs* time at constant voltage diode MS-5; cold tungsten needle shaped cathode of radius 1.5×10^{-5} cm, plane tungsten anodes, 1720 glass envelope. Curve A, 1000 hours of unattended dc operation at a current density of 10^7 a/cm^2, average power of 35 watts, 10^{-9} cm^2 emitting area 4.66 kv; curve B, emitter reconditioned by brief heat flash and then operated as shown to establish reproducibility of first run; curve C establishes stability at lower current, 4.36 kv.

The needle shaped tungsten field emitter is shown in Fig. 2. The emission was restricted to an area of 10^{-9} cm^2 on the hemispherical tip of radius 2×10^{-5} cm. Thus the average beam power per unit cathode area in the foregoing test was 35 billion watts/cm^2. This number may be exploited to provide either extreme miniaturization or unusually high power. For example, a field emission gun small enough to be inserted in a common hypodermic needle (Fig. 3) can provide 1 kw of peak power. Thus a field

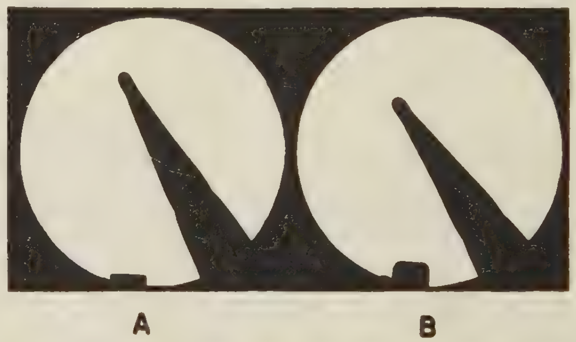

Fig. 2—Electron microscope shadowgraphs of a typical field emitter; *B* shows emitter rotated 90° from position of *A*; magnification 3000 ×.

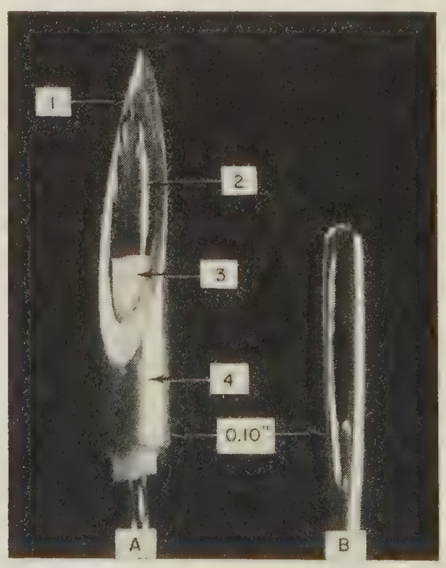

Fig. 3—*A* shows a cutaway view of miniaturized field emission gun with cathode needle 1, filament support 2, ceramic insulator 3, anode 4 (the latter is a standard hypodermic needle with approximately 0.030" i.d.); *B* is the eye of a common sewing needle.

* Manuscript received by the PGMIL, October 29, 1959.
† Linfield Res. Inst., McMinnville, Ore.
[1] E. E. Martin, J. K. Trolan and W. P. Dyke, "A stable high density field emission cathode" (to be published).

emission gun may have transistor size but transmitting tube power. On the other hand a group of such cathodes, or even wires, placed in a high electric field, can provide very high currents and power. A 40-needle comb has given peak power of 3 megw during microsecond intervals;[2] a cold tungsten razor edge has yielded 30 megw peak; a group of wires is used in a 300-megw flash X-ray tube now in production.

It appears that the field emitter is also capable of considerable average power. The techniques which were used to extract a beam power of 35 watts from a single needle in Fig. 1 have been extended to a cathode composed of a group of needles. The latter is presently undergoing tests at an average power of 120 watts with promising stability.

Free electrons are contained at a metal surface by an electrical potential barrier whose height, a few electron volts, is called the work function. In conventional cathodes the electrons are given sufficient energy (heat, light, kinetic) to surmount the barrier and escape into vacuum to form an electron beam. In the case of field emission, the electrons penetrate the surface barrier when it is thinned and reduced in height by the presence of a strong electric field. It is not necessary to supply the electrons with energy to cause field emission, *i.e.*, the cathode may be cold; in fact, high density field emission has been obtained[3] from diodes immersed in liquid helium (4°K). For most practical purposes the high density emission is independent of temperature at all levels which the metallic needle will withstand. Of course an obvious advantage of the cold cathode is that heater power and its supplies are avoided.

The field emitter is distinct from the cathode introduced by Dobischek.[4] While both are cold cathodes in which a high electric field is used to extract electrons into vacuum, the field emitter has a clean metallic surface while the Dobischek cathode has a MgO coating. In field emission the electric field is applied and controlled by an electrode external to the cathode, whereas in the other case the field is in a large part due to positive charges on the MgO insulating layer. In field emission, the current response is instantaneous and follows the applied electric field at least to the demonstrated frequency of 36 kmc; the MgO cathode must be given a positive surface charge in order to establish the emission, and this requires an initiating mechanism such as electron bombardment; the MgO cathode is reportedly limited to relatively low frequencies. There is also an important difference in the energy distribution of the emitted electrons in the two cases which has a bearing on noise, electron optical aberrations, etc. The field emitter has a relatively narrow distribution, *e.g.*, 0.2 to 0.3 ev (determined by the electron supply function and by the shape of the surface potential barrier) whereas in the other cathode the energy distribution is said to be considerably larger. Of course a major difference between the two cathodes is the unusually high field emission current density which was mentioned above.

The electric field required in field emission is high, *e.g.*, $10^7 < F < 7 \times 10^7$ v/cm; however, the corresponding voltages are not necessarily large, depending on the choice of cathode geometry and work function. With improving techniques in cathode fabrication by electropolishing,[5] the voltage range over which useful, controlled field emission has been obtained in the laboratory has been extended from 320 to 500,000 volts. The lower voltages require tip radii of the order of 10^{-6} cm and at the highest voltages radii of 10 microns have been used. In the case of a single tungsten needle of cone angle 10° and spacing 10 mils from a planar anode, the relationships between current, voltage, conductance, and radius are shown in Fig. 4 for an emitted current density close to the maximum consistent with long life and electrical stability of the pulsed cathode, *e.g.*, 10^7 amperes/cm^2 for an average cathode size. Low conductance devices like cathode ray tubes may employ the single needle cathode; however, many applications require higher conductance which can be obtained from a group of needles operated in parallel. The dc beam perveance and power

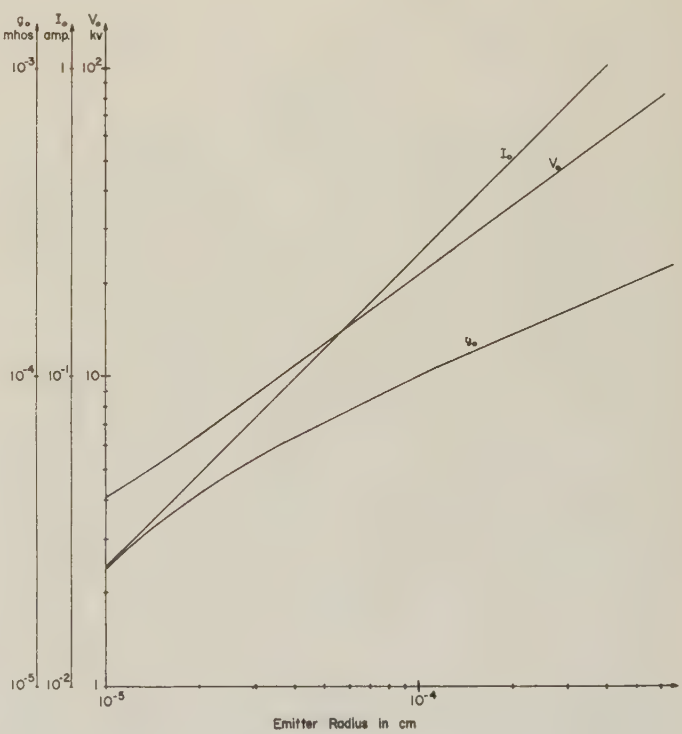

Fig. 4—Variations with field emitter tip radius of current I_o, beam voltage V_o, and ac conductance g_o for a current density of 10^7 a/cm^2, a 10-mil anode-cathode spacing, and $\phi = 4.5$ ev (tungsten). Values include corrections for space charge.

[2] W. P. Dyke and W. W. Dolan, "Field emission," *Advances in Electron Physics*, vol. 8, pp. 89-184; 1956.
[3] R. Gomer, *J. Chem. Phys.*, vol. 20, p. 1772; 1952.
[4] D. Dobischek, *Business Week;* January 31, 1959.
A. M. Skellett, B. G. Firth, and D. W. Mayer, "The magnesium oxide cold cathode and its application in vacuum tubes," Proc. IRE, vol. 47, pp. 1704-1712; October, 1959.

[5] W. P. Dyke *et al.*, *J. Appl. Phys.*, vol. 24, p. 570; 1953.

are shown as a function of number and size of the needles in Fig. 5. For example, the perveance commonly found in klystrons can be exceeded by use of a sufficient number of needles.

In order to control the current density within 10 per cent from needle to needle, the individual geometries must be held within 1 per cent, which may at first hand seem to be an imposing problem for refractory objects of micron size. However, surface forces can be used to shape the heated emitter in a highly controlled manner leading to multiple needle "combs" as in Fig. 6 which can typically provide 0.1 to 1.0 ampere at 1 to 10 kv respectively. As was noted above, larger combs[2] have given 30 amperes at 100 kv. Obviously, groups of combs may be employed for further increases in conductance.

Field emission was discovered in 1897 by R. W. Wood.[6] In the late 1920's, Millikan and Lauritsen[7] obtained the first controlled emission and established the empirical law

$$I = A \exp(-B/V), \tag{1}$$

where I is current, V is voltage and A and B are constants. More recently, a refinement of (1) has been derived[8,9] from wave mechanical considerations and verified experimentally[10] for current densities in the range $100 < J < 4 \times 10^8$ a/cm². A correction of the theory for the effects of space charge[11] was found necessary at densities above 10^6 a/cm², and resistive heating[12] of the emitter tip by the emission current was shown to set a practical limit on current density[13] at the order of 10^8 a/cm² for pulsed emission and about 10^7 a/cm² for dc emission.

The strongly nonlinear characteristic shown in (1), together with the high current density and small size of the cathode, have recently been used successfully to operate triode and tetrode structures at wavelengths in the range 3 cm to 8 mm. Of course those simple RF structures offer a number of advantages, and their extension to the indicated wavelength range may be of some practical value. When a field emitter is inserted in a resonant cavity, the oscillating electric field controls the emission and electrons are emitted in bunches in phase with the electric field; in turn, the beam may be energized and used to amplify an RF field. A simple triode structure is illustrated in Fig. 7 and has been given the name FEMITRON in view of its dependence on field emission. The field current-voltage relationship in the presence of both bias and RF voltages is shown in Fig. 8. The properties of the device depend

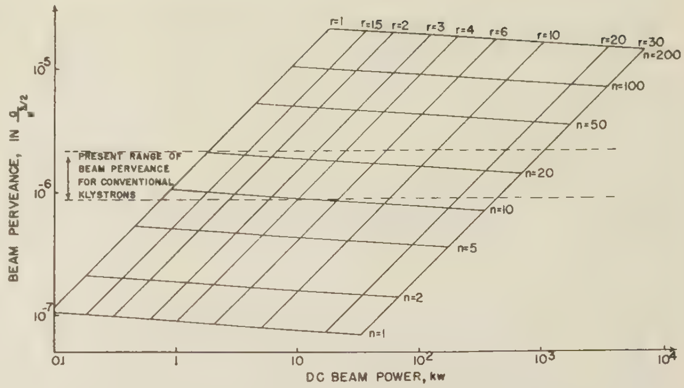

Fig. 5—Beam perveance and dc power for multiple needle field cathode, as a function of needle number n and tip radius r (in 10^{-5} cm units). Beam perveance is increased by increasing the number of needles, and may substantially exceed that found in conventional klystron beams.

Fig. 6—Mutiple needle field emission cathode, tungsten needles on tungsten wire support.

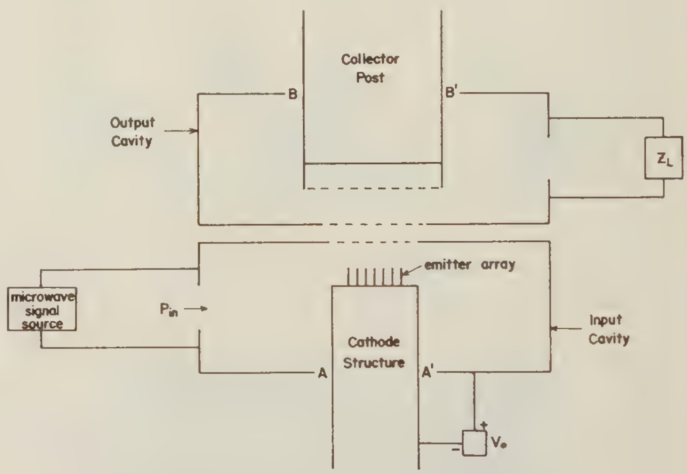

Fig. 7—Schematic diagram of the FEMITRON.

strongly on the harmonic analysis shown in Fig. 9. The detailed analysis of FEMITRONS has been presented elsewhere[14] and only a brief summary will be included here.

An extensive experimental program was undertaken to test the validity of (1) at microwave frequencies.[15] Electric fields at 10 kmc have been impressed on single needle field emitters in input structures such as Fig. 7 and the resulting field emission beam has been extracted and examined in detail. It is observed that the electron beam is

[6] R. W. Wood, *Phys. Rev.*, vol. 5, p. 1; 1897.
[7] R. A. Millikan and C. C. Lauritsen, *Proc. Natl. Acad. Sciences*, vol. 14, p. 45; 1928.
[8] R. H. Fowler and L. W. Nordheim, *Proc. Roy. Soc. (London) A*, vol. 119, p. 173; 1928.
[9] L. W. Nordheim, *Proc. Roy. Soc. (London) A*, vol. 121, p. 626; 1928.
[10] W. P. Dyke and J. K. Trolan, *Phys. Rev.*, vol. 89, p. 799; 1953.
[11] J. P. Barbour, *et al.*, *Phys. Rev.*, vol. 92, p. 45; 1953.
[12] W. P. Dyke, J. K. Trolan, E. E. Martin and J. P. Barbour, *Phys. Rev.*, vol. 91, p. 1054; 1953.
[13] W. W. Dolan, W. P. Dyke, and J. K. Trolan, *Phys. Rev.*, vol. 91, p. 1054; 1953.

[14] F. M. Charbonnier, J. E. Henderson, and W. P. Dyke, "Theory of the FEMITRONS, a class of field emission microwave devices, Part I," submitted to PROC. IRE.
[15] J. P. Barbour, F. M. Charbonnier, and W. P. Dyke, "Experimental study of field emission at microwave frequencies, Part II" (to be published).

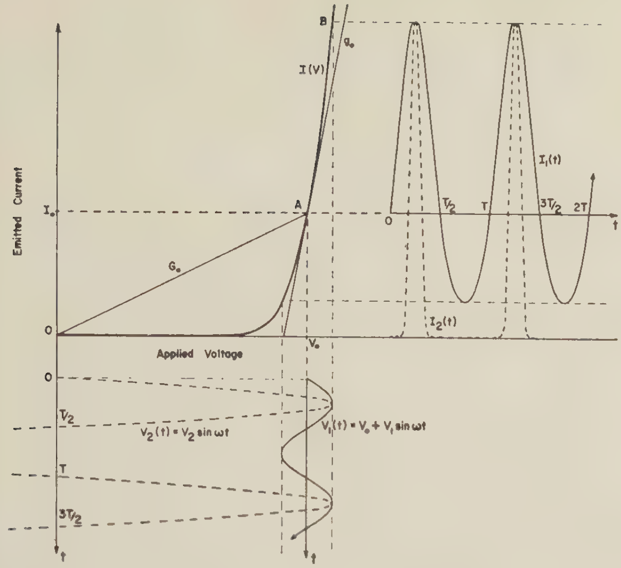

Fig. 8—Emission bunching of the field emission beam. The field emission characteristic $I(V)$ and the selected operating point A determine the dc conductance G_0 and the ac conductance g_0. The current waveforms $I_1(t)$ or $I_2(t)$ correspond to the application of the voltages $V_1(t)$ or $V_2(t)$. T is the period of the RF component of the applied voltage.

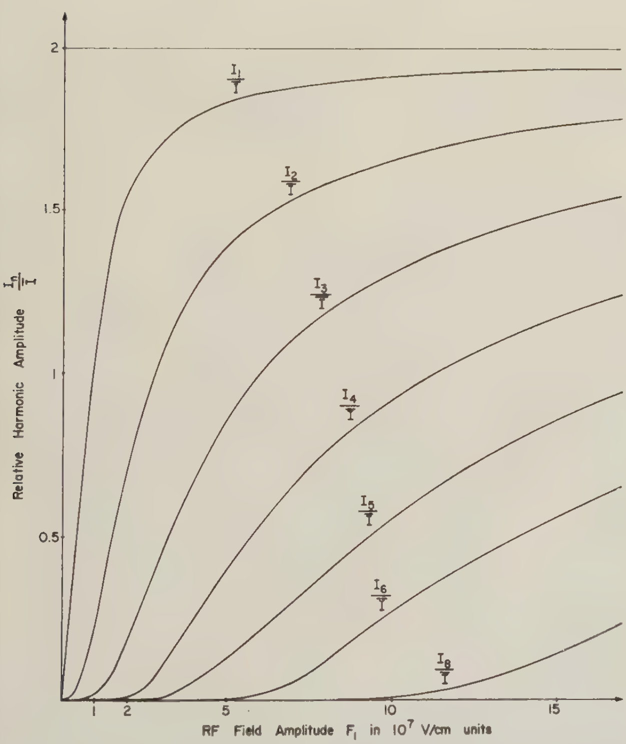

Fig. 9—Ratio of harmonic to dc amplitude in the emission bunched electron beam, as a function of the RF field F_1 at the cathode tip. For each value of F_1, the dc bias field F_0 is adjusted to maintain a constant resistive heating of the emitter tip.

tightly bunched upon emission and may be used immediately; neither velocity modulation nor a drift space is necessary. Hence the FEMITRON is a short transit device having, for example, 40 mils over-all beam length from cathode to collector at X-band. As a result, phase stability is high and no magnetic focusing is required. When the emergent beam was incident on a phosphor screen, the characteristic field emission pattern was used to identify the location, size and surface condition of the emitting area in the usual manner; also, the detail of the pattern provided an indication of the level of the current density. Average current was also measured and was found to depend on applied RF voltage in the manner expected from (1). A velocity analysis of the emergent beam was made and revealed the energy distribution expected from Fig. 9, since the beam extracts energy from the RF field in the input cavity and the electron energy is therefore a function of beam density. Measurement of this function gave further evidence of the validity of (1) at microwave frequencies.

The harmonic analysis of Fig. 9 has also been experimentally tested in several ways. As the dc cathode bias voltage V_0 was increased, Fig. 7, the cathode ac conductance and the fundamental component in the field emission beam also increased in amplitude. The cavity was therefore increasingly loaded by the beam, causing corresponding variations in the coupled impedance and the VSWR in the input guide. Agreement between predicted and observed combinations of input power and VSWR gave an indication of the validity of the fundamental component as predicted in Fig. 9. Also, the expected relationship between input and output power was observed when the FEMITRON was operated as a two-cavity amplifier. Other harmonics were measured and verified when the FEMITRON was operated as a mixer (with two input signals at 10 kmc and 28 mc respectively) and as a frequency quadrupler from 3-cm to 8-mm wavelength.

The validity of the field emission law (1), and of the analysis and operation of FEMITRON devices at microwave frequencies, thus appears to be established by experiment. In the tests reported above, single-needle cathodes were used in order to facilitate the determination of field, current density, and work function from measured power, current, and voltage. It may be of some interest to note the predicted performance when higher conductance cathodes of the type shown in Fig. 6 are used. The extrapolation may not be wholly unreasonable since the proposed conductance has been demonstrated, and in the present short transit device space charge debunching is not expected to deteriorate high power performance as it does in conventional long transit devices. When 20 needles of radii 8×10^{-5} cm, unity beam coupling and beam transmission, and typical re-entrant cavity characteristics are assumed, Fig. 10 indicates that the FEMITRON amplifier can be a high efficiency, moderate gain device at high peak power. Electronic efficiencies of 40-80 per cent appear possible due to the large ratio $I_1/\bar{I}$ shown in Fig. 9, *i.e.*, to the unusually effective electron bunching which can be achieved because of the highly nonlinear field emission characteristic. Further increase in over-all efficiency is provided by cold cathode operation. Gain, of the order of 10 db in the present simple embodiment, may be at least doubled by use of improved input structures.

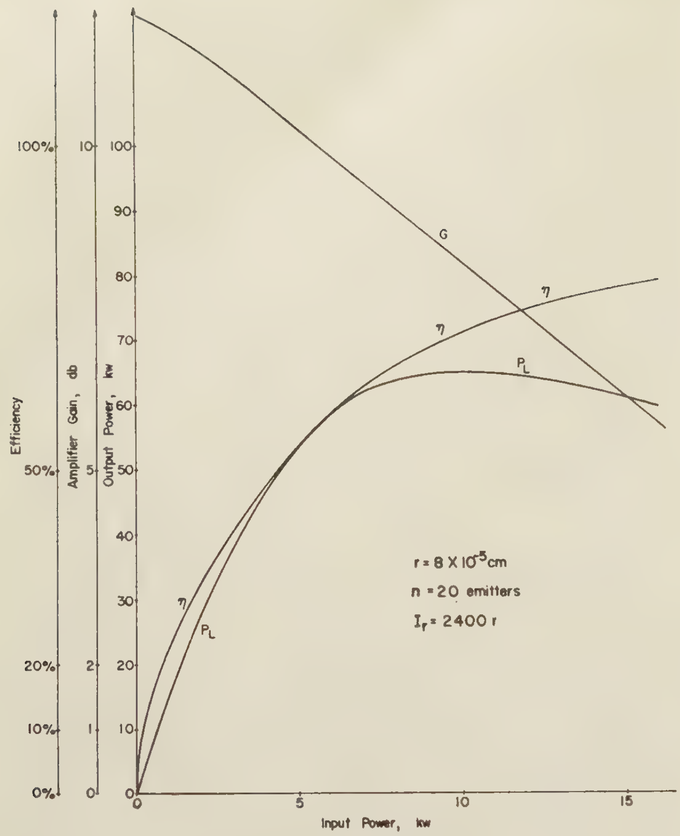

Fig. 10—Calculated performance of a FEMITRON amplifier with biased collector post for a 20-emitter cathode ($r = 8 \times 10^{-5}$ cm) and 1 per cent bandwidth.

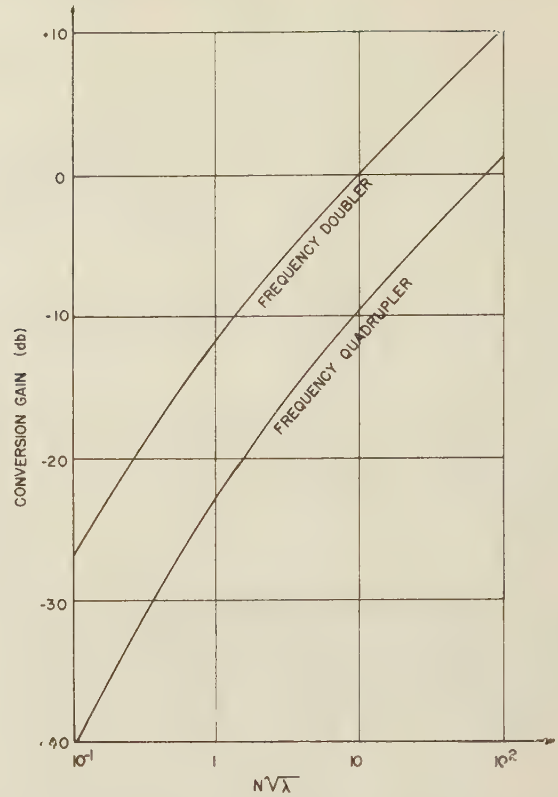

Fig. 11—Calculated conversion gain of a two-cavity field emission frequency multiplier *vs* $N \sqrt{\lambda}$, where N is the number of needles, and λ is the input wavelength in centimeters. The beam transmission and beam coupling coefficients are assumed to be unity, and the optimum cathode bias voltage is used in each case.

Because of the small cathode size, the FEMITRON and similar structures can be scaled to millimeter wavelengths, where sufficient starting currents and useful power outputs may be predicted because of the high current density.

In a similar manner, it is interesting to calculate the gain of frequency doublers and quadruplers when multiple needles are used. Fig. 11 shows, that for a sufficient number of needles, unit gain may be achieved in both cases at powers above about 1 kw. In a similar way, frequency mixing without loss is expected in a two-cavity device. Thus, the FEMITRON may extend to high power several functions which until recently have been restricted to crystals at low power. The ability to mix, modulate and multiply high power microwave signals may be useful in sophisticated communication systems.

Any device has its disadvantages, and the FEMITRON is of course no exception. For example, it requires high vacuum, *e.g.*, 10^{-9} to 10^{-12} mm of Hg when the cold cathode is used; however, such pressures can be achieved by vaporion techniques.[1] Alternatively, the cathode may be operated at more conventional pressures by maintaining it at an intermediate temperature;[16] however, in this case pulsed operation at a duty cycle not exceeding about 10 per cent is required. Current density must not exceed the critical level of the order of 10^8 a/cm^2 set by resistive heating[13] of the emitter tip by the emission current; this may be achieved by keeping the applied voltage below a corresponding value. The cold cathode must be reconditioned infrequently by a brief heat flash, say once each 100 to 1000 hours depending on power level and environment, in order to remove impurities and roughness; however, given such reconditioning, the cathode life appears to be indefinite. Operating periods for laboratory diodes with cold cathodes have exceeded 12,000 hours and life is probably much longer. The absence of high temperature and the use of refractory cathode material apparently avoid the life terminating mechanisms common to thermal cathodes, *e.g.*, evaporation, diffusion, growth of boundary layers, chemical changes, etc.

It appears that field emission will also be useful in another class of applications, *i.e.*, electron optical devices which require high resolution, speed and brilliance. A cathode-ray tube with a 1-mil spot and a 0.3 per cent beam efficiency has been operated, and beam currents up to 100 microamperes appear to be within the present state of the cathode art. Spot size of 1 micron appear possible and in general the field emitter is expected to give larger beam currents than thermal emission at spot sizes below about 1 mil. This is possible because the electron optical brightness,

$$B = \frac{J_0}{\pi} \frac{eV}{\overline{E}_t}, \qquad (2)$$

[16] W. P. Dyke *et al.*, "Life and electrical stability of the heated field emission cathode" (to be published).

in amperes per cm² per steradian is thought to exceed that of the thermal emitter by about six orders of magnitude. In the case of thermal emission the Langmuir relation applies:

$$J_x = J_0 \frac{eV}{kT} \sin^2\gamma, \tag{3}$$

where J_x is the current density at a point x, J_0 is the current density at the cathode surface, V is the applied voltage, T is the cathode temperature and γ is the angle between the electron velocity and the optical axis. In the case of field emission a similar relationship is assumed:

$$J_x = J_0 \frac{eV}{d} \sin^2\gamma, \tag{4}$$

where d is the width of the energy distribution of the field emitted electrons, *e.g.*, of the order of 0.2 to 0.3 ev. When "present state of the art" values of the cathode parameters are used, (3) and (4) may be used to compare the probable performance of field and thermal emission cathodes. A comparison is shown in Fig. 12 in which the assumptions include a typical deflection lever arm of 10 inches, identical electron lenses limited by spherical aberrations in both cases, and sufficient anode voltage to overcome space charge effects. The comparison indicates that field emission may provide useful beam currents at spot sizes smaller than those now in common practice.

In other applications requiring very high beam currents in moderate spot sizes, it may be of interest to note that it has been possible electrostatically to focus the entire emission from a tungsten needle into a distant spot of the order of a millimeter in diameter. Considerably smaller spots are possible with magnetic focusing. Applications may be expected in oscillography, data storage, microscopy, and beam deflection devices.

The main disadvantage of the field emitter in electron optical applications, in addition to the high vacuum that is required when the cathode is cold, is the level of grid voltage needed to modulate the beam density. At the present state of the cathode art, about 1000 volts are required to cause emission for needle geometries which are readily fabricated and handled in practice. However, in view of Fig. 8, a much smaller voltage change will modulate the emission. If the current density is $J_0 = 10^7$ a/cm² at the voltage V_0, it is $J_0 \times 10^{-2}$ at 0.7 V_0 and $J_0 \times 10^{-6}$ at 0.4 V_0. If future tests reveal stability for low work function cathodes, the required voltages may be reduced by an appreciable factor, *e.g.*, 2 or 3, from the levels quoted. In laboratory experiments, emission has been drawn at voltages as low as 320 volts.

Early experimenters foresaw the application of field emission to X-ray generation.[17] Recent improvements in stability and current encouraged the application of comb emitters (Fig. 6) to a 3-megw tube which gave microsecond shadowgraphs at 2 feet through small biological

[17] J. E. Lillienfeld, U. S. Patent No. 1,559,714; 1920.

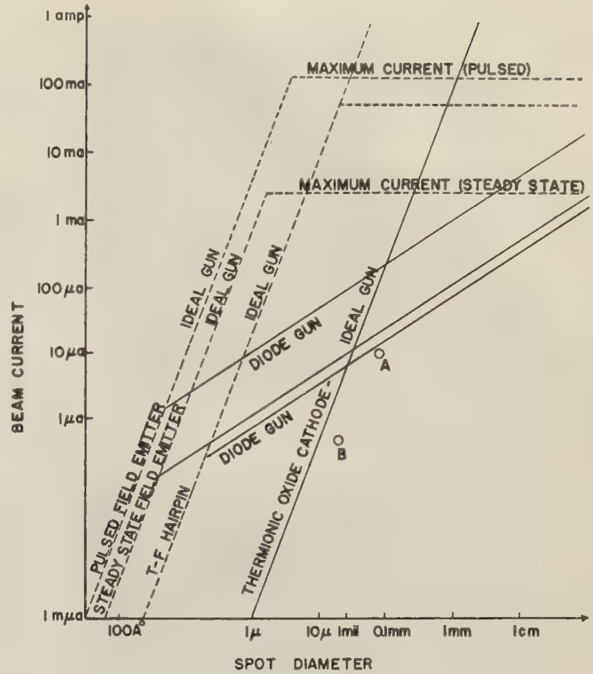

Fig. 12—Comparison of the thermionic and field cathodes in cathode-ray tubes and other flying spot applications.

specimens.[2] More recently,[18] T-F emission from wire cathodes has increased peak power to 300 megw giving 0.2-μsec X-ray exposures at film-to-source distances of 22 feet in air, or 2 feet through 4 inches of aluminum.

A flash X-ray tube requires large current in order to produce sufficient X-ray intensity for photographic exposures in short time periods. For good optical resolution, the X-ray spot size, and therefore the cross section of the electron beam, must be small. In the FEXITRON X-ray tube[19] a beam current of 1000 amperes has a cross section of approximately 1 cm² at the anode (0.7 × 1.5 cm); when viewed end on this strip source has an apparent "spot size" of 2 × 7 mm at the object. The geometric and time resolution of the FEXITRON are apparent in Figs. 13 and 14.

The field emission techniques which are used to draw such large currents also show how to avoid voltage breakdown at high field strengths; thus, it is possible to generate and use unusually high power in small volumes. In the FEXITRON, anode-cathode spacing is 0.5 cm; the cathode consists of five 10-mil tungsten wires; the applied voltage is 300 kv. The beam volume is 0.5 cm³ and the peak power is 300 megw; thus the tube power per unit beam volume is 600 megw/cm³. The anode electric field is approximately 6×10^5 v/cm and the field at the cathode is in excess of 10^6 v/cm. During the 0.2-μsec pulse, the anode temperature increases from room temperature to 3000°K. The current density at the cathode is 2000 amperes/cm² and the current density averaged over the 1 cm² beam at the anode surface is 1000 amperes/cm²; the perveance of

[18] F. J. Grundhauser, *et al.*, presented at *Field Emission Symposium;* 1959.
[19] Manufactured by Field Emission Corp., McMinnville, Ore.

(a)

(b)

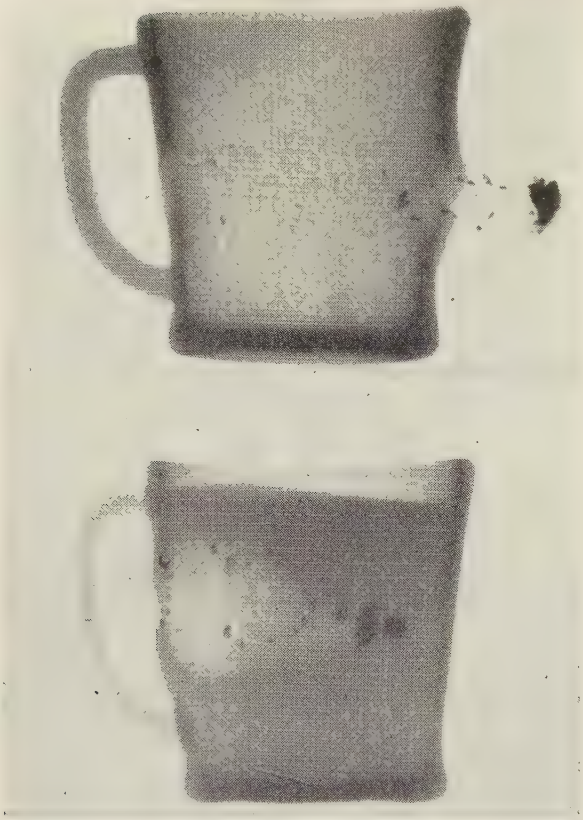

Fig. 13—Field emission X-ray (FEXITRON). (a) Radiograph of a .22-caliber long rifle bullet striking an ordinary glass coffee mug. 225 kv, 750 amperes, 0.2 μsec, FTSD = 12 feet, Patterson type 245 intensifying screen-Kodak Blue Royal X-ray film combination. (b) Glass mug filled with water. 275 kv, 850 amperes, 0.2 microsecond, FTSD = 12 feet.

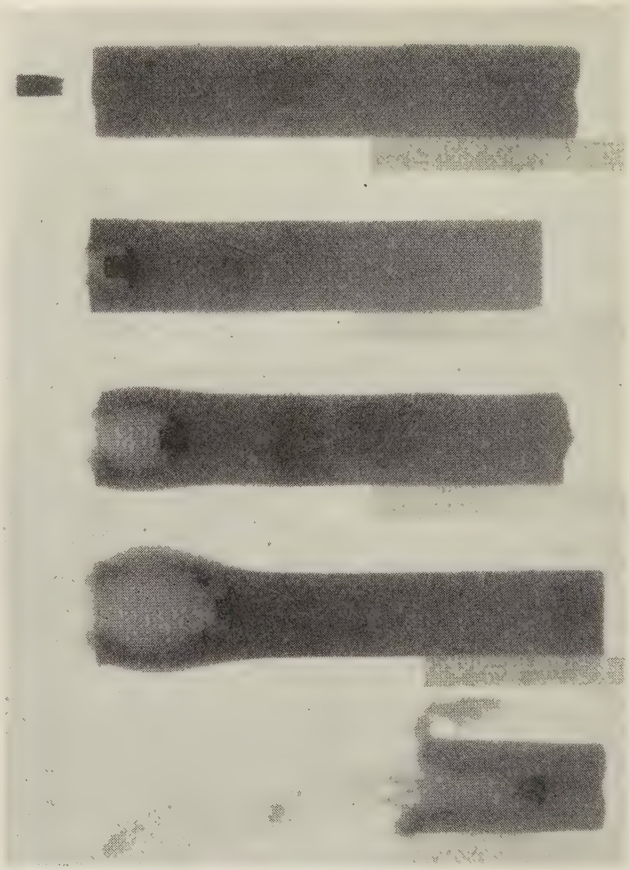

Fig. 14—A composite of five radiographs of a .22 caliber long rifle bullet penetrating modeling clay. 225 kv, 750 amperes, 0.2 μsec, FTSD = 12 feet, Patterson type 245 intensifying screen-Kodak Blue Royal X-ray film combination.

the tube is 6×10^{-6} amperes/volts$^{3/2}$. The combined values of these parameters are somewhat above common practice and are made possible by field emission techniques, clean surfaces and vacuums of the order of 10^{-12} mm of Hg. Incidentally, if the same techniques can be scaled to smaller structures, and that should prove to be easier rather than more difficult, then on the basis of 600 megw/cm^3 one might expect to be able to handle, without breakdown, a peak power of the order of 0.1 megw in a resonant cavity at a wavelength of 1 mm.

An advantage of the FEXITRON is its reliability on a pulse-to-pulse basis (Fig. 15) as compared to the earlier vacuum arc flash X-ray tubes in which the wave shape, jitter, and yield are reported to be less consistent.[20]

The possible medical applications of field emission X rays may also be of interest. A thin X-ray anode has been wrapped around a mouse and used to generate an X-ray dose rate of 2.5×10^7 roentgen/second for a microsecond interval, and with this dose to detect a biological effect. A high intensity, variable duty cycle, pulsed X-ray system is also under construction to extend the observations of Witte[21] who observed that duty cycle may alter the relative biological effect at constant dose. The high current X-ray tube also makes possible light weight, portable, battery operated units which are the radiographic equivalent of the visual strobe light now commonly used in photography. Because the generation of X rays is less efficient than light and requires more voltage, X ray units will be some-

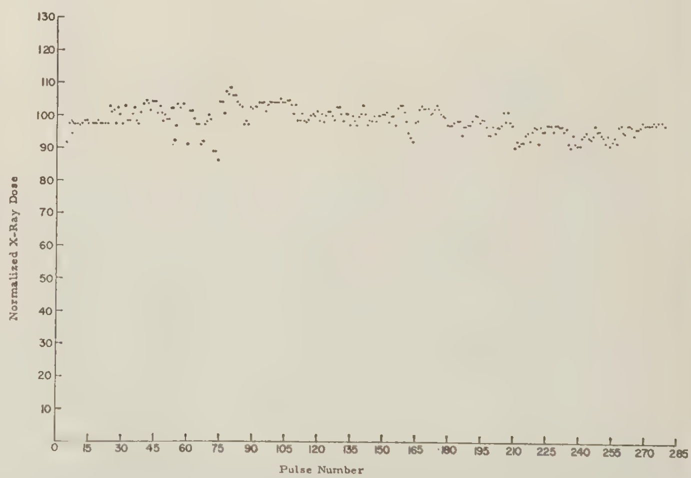

Fig. 15—Graph of normalized X-ray dose illustrating reliability of a standard production FEXITRON X-ray tube #301, type T-300-1000-0.2 at full power: 300 kv, 1000 amperes, 0.2 μsec; graph shows typical 280-pulse sequence from longer total life; dose read on Cambridge dosimeter #214410 at beam direction of maximum intensity *vs* spot size.

[20] P. T. G. Flynn, *Proc. Phys. Soc. (London) B,* vol. 69, no. 7, 1956.

[21] E. Witte and R. Sigmund, *Strahlentherapie,* vol. 88, pp. 384-394; 1952.

what heavier than the present photographic units; however, a 45-pound chest X-ray unit appears to be feasible. To the extent that it is possible to miniaturize X-ray tubes as in Fig. 3, the source may be injected for localized therapy and diagnosis. Of course, as Marton[22] and Pattee[23] have pointed out, the X-ray microscope may be extended to higher intensities and to shorter exposure times by use of a field emission needle-shaped cathode.

Field emission has also been applied to experimental models of rectifiers, transducers, and voltage control tubes; other applications such as T-R tubes and microwave reflex oscillators with distinctive properties are under study. While space will not permit a detailed discussion of these applications, it may be of interest to comment on the voltage control tube in passing. In view of (1), a small change in applied voltage causes a large change in field emission current which in turn can be used to measure and to control the voltage. When a field emission tetrode is used as a sensing element in a conventional circuit it is possible to control a kilo-voltage to 0.1 per cent over a 30 per cent change in voltage (Fig. 16). The device can have high speed (electrons in vacuum instead of gas) and is expected to be relatively insensitive to radiation. Perhaps its most significant property is that it is an absolute device; *i.e.*, when geometry and work function are specified, each value of current corresponds to a single value of voltage. Because of these properties it will be possible to perform certain functions which have heretofore been difficult. For example, a field emitter may be inserted in the output waveguide of a radar and used to measure or to control the output RF voltage on a pulse-to-pulse basis. In this connection it is important to note that the field emitter has a demonstrated response to RF fields at frequencies up to 36 kmc, and it is expected that (1) will be valid at even higher frequencies.

History records that the development of each new electron source is followed by its application to a family of new electron devices which more often complement than compete with existing technology. The field emitter may now be applied to the several new devices which have been described above. If the milliampere hours of unattended cold cathode operation continue to increase at the present rate (Fig. 17) a number of other applications may be possible in a year or two.

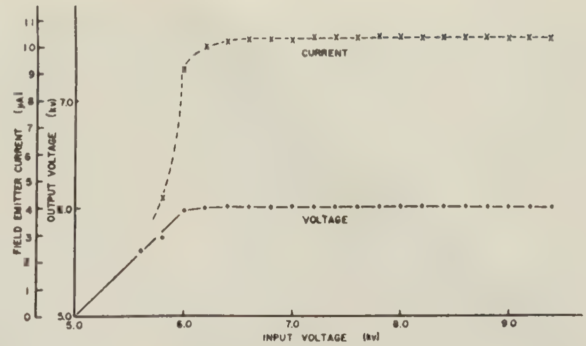

Fig. 16—Voltage regulator response. The variation in output voltage for a 50 per cent change in input voltage was too small to be measured directly, but an indirect determination of 0.06 per cent was obtained from the corresponding 1 per cent change in field emitter current.

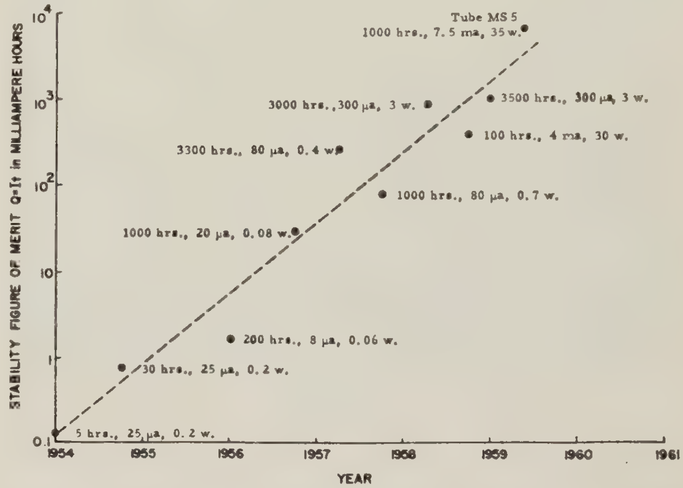

Fig. 17—Improvement with time of the stability figure of merit $Q = It$ for a single needle cold field cathode operated dc at fixed applied voltage. I is the dc emitted current, and t is the period of continuous operation with cathode reconditioning. The cathode current density in tube MS 5 exceeds 10^7 a/cm^2. The rate of progress over the past 5 years has been exponential with a time constant of ½ year.

Acknowledgment

The present work was initiated in 1946 through a series of grants from Research Corporation. In 1948 the assistance of ONR was sought and received to explore the basic properties of high density field emission; most of the basic knowledge relating to this new technology was acquired under this initial and continuing support and has been presented in a recent review article.[2] The high frequency devices and nonmedical X-ray applications reported here have for the most part been supported by the Bureau of Ordnance of the U. S. Navy through the Applied Physics Laboratory of the Johns Hopkins University; the Bureau of Ships has also supported part of this phase of the work. The Air Force has supported in part the development of cold cathode stability and the early work on cathode ray tubes. The medical X-ray applications have been developed for the Army Medical Corps and the frequency multiplier for the U. S. Army Signal Corps which has also supported studies in basic chemistry relating to emitter fabrication.

The present report also summarizes the substantial and much appreciated efforts of numerous individuals on the Linfield Research Institute staff to whom much credit for this new technology belongs.

[22] L. Marton and R. A. Schrack, *Abstracts, Westinghouse Field Emission Symposium*, Pittsburgh, Pa.; November, 1954; and L. Marton, *Natl. Bur. Standards Circ.*, vol. 527; 1951.

[23] H. H. Pattee, Jr., *Phys. Rev.*, vol. 92, p. 541A; 1953.

The ONR Program in the Electronics Research Laboratory of the University of California, Berkeley*

SAMUEL SILVER†

I. Introduction

THE ONR program in the Electronics Research Laboratory started in 1949 with a project in the microwave antenna field. Since then, as the potentialities of the electrical engineering department developed, sponsorship was extended to a number of other fields and at the present time the program comprises: 1) propagation and radiation, 2) circuit analysis and synthesis, 3) information theory, 4) solid state electronics, and 5) upper atmosphere and solar radiation investigations. The program from its inception has been one of basic research and has been conducted in the tradition of university research: faculty motivation, faculty direction, and graduate student participation as an integral part of the graduate study program. The usefulness of the program to the Navy stems from the awareness of the faculty investigators of the operational needs of the Navy. The exchange of ideas between faculty investigators and members of the Office of Naval Research, and of operational units such as Bureau of Ships and Bureau of Aeronautics, is an important factor in the situation in giving the basic research motivation and a direct outlet into applied research and development. The emphasis and direction of the program has shifted over the years with the recognition of new needs. To mention but two: Studies of diffraction and of slot antennas were related to new designs of antenna systems for aircraft carriers; investigations of scattering cross sections were given a strong impetus by problems in missile guidance technology. In the following we shall describe the current research activity and illustrate its relevance to the Navy's program in space technology.

In a review of the type given here it is, of course, necessary to be restricted to highlights and general aspects. The specific research problems delineated during the presentation are but illustrations of a much larger number of specific studies. The most important feature, however, which should be noted is the breadth of the program supported by the Office of Naval Research and how, while it is a program in basic research particularly adapted to the sphere of activity of an educational institution, it is relevant to and does indeed have a proper place in the Navy's program of space research.

* Manuscript received by the PGMIL, October 29, 1959. The faculty investigators presently involved in the program are Profs. Angelakos, English, Kuh, Pederson, Rumsey, Silver, Thomasian, and Wang.

† Director, Electronics Res. Lab., Dept. of Elec. Engrg., Univ. of Calif., Berkeley.

II. Propagation and Radiation

The activities of this project encompass general theory, investigations of scattering cross sections, plasmas and ferrites. Illustrative of the work in general theory is the study of the boundary conditions that are required to specify an electromagnetic field and the methods of determining the field in space from the boundary conditions. This study of generalizations of the so called Huygens Principle may seem far removed from any practical application such as missile guidance or satellite guidance and tracking. However, consider the following class of problems: It is necessary to provide a missile with a tracking system, or a satellite vehicle with an antenna system as part of a satellite relay system. Let us suppose that the desired performance could be achieved by a paraboloidal antenna or a family of horns or combinations of such antennas if the housing of such antennas were of no consequence. But the difficulty is precisely that the antennas must be housed within the vehicle and the interaction between the antennas and the housing is such a large perturbing factor that the performance becomes degraded to an unacceptable level. The solution which immediately suggests itself is to replace the internal antenna system by a flush-mounted antenna system. Such a system may be, for example, an array of slots. The radiation problem then can be formulated as one of establishing a surface distribution which will produce the same exterior field. But Huygens' Principle pertains to just this matter. (See Fig. 1.) One form of the principle states that if over the surface S we produce a tangential electric distribution corresponding to that produced over the geometric surface by the free-space antenna system A, we shall generate the same field exterior to S produced by A in free space. A tangential electric field distribution can be associated with surface distribution of "magnetic" currents, which in turn are approximately realizable by distributions of slot antennas. Thus the Huygens' Principle provides a starting point in the design of a surface antenna system. More generally, it provides a reference system which of itself may not be practically realizable because of the technical difficulties of feeding, switching (should scanning be required), and the limitations on polarization imposed by the shape of the slot radiators. The reference system affords a base for comparing designs that can only approximate the solution; it may even provide information which may indicate that a satisfactory solution cannot be realized at all.

Also in the missile and satellite field, there is the im-

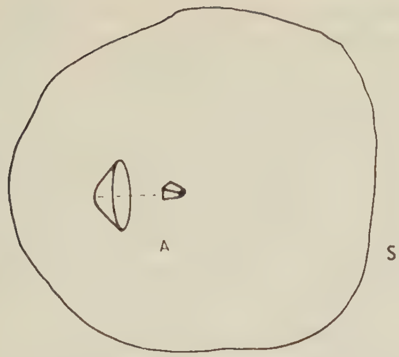

Fig. 1—On the application of Huygens' principle.

portant problem of tracking by observers on ground sites or on other vehicles. One need only recall the extensive work that was done on scintillation noise in conical lobing tracking systems in the early stages of the missile program to appreciate the magnitude of the problems involved. The basic information required for analyzing and solving the operational problems concerns the scattered field produced by the object. It is not only necessary to know the back scattering to the source of radiation but also the scattering in all directions. Corresponding information is highly important in the analysis and design of space radio relay systems. A great deal of work has been done in our laboratory and in a number of others on the analysis of scattering of waves by objects of various shapes. The subject is still, however, far from closed. Theory is in an excellent state with respect to objects whose dimensions are small compared with the wavelength and for certain special geometrics (spherical, circularly cylindrical, ellipsoidal) when the dimensions are very large compared with wavelength. When the objects have shapes other than the ideal ones, and quite generally when the dimensions are comparable with the wavelength, theory falls short of being satisfactory; indeed the problem at the present time is the two-fold one of gathering reliable data upon which theory can be built and of making definitive tests of new theoretical methods and results. Inasmuch as both missiles and satellite technologies involve a very broad spectrum of radiofrequencies from the VHF to the microwave region, it is clear that the entire realm of scattering theory is involved.

The measurement of scattered fields with precision and accuracy is one of the most demanding types of measurement to make. It has been a major project in our laboratory for a number of years, and was very likely the first anywhere in which an investigation and successful measurement was made of forward scattering, that is, in the region of the geometrical shadow. The total field in space is a combination of the primary field and the field produced by induced currents (conduction or polarization currents) and it is necessary to separate the component parts in order to obtain the scattered field alone. The latest form of instrumentation developed in our laboratory utilizes a large ground plane as shown in Fig. 2. This scattering range is suited particularly to objects which are figures of revolution or which have two orthogonal planes of symmetry. It is possible to measure the complete scattered field in the planes of symmetry.

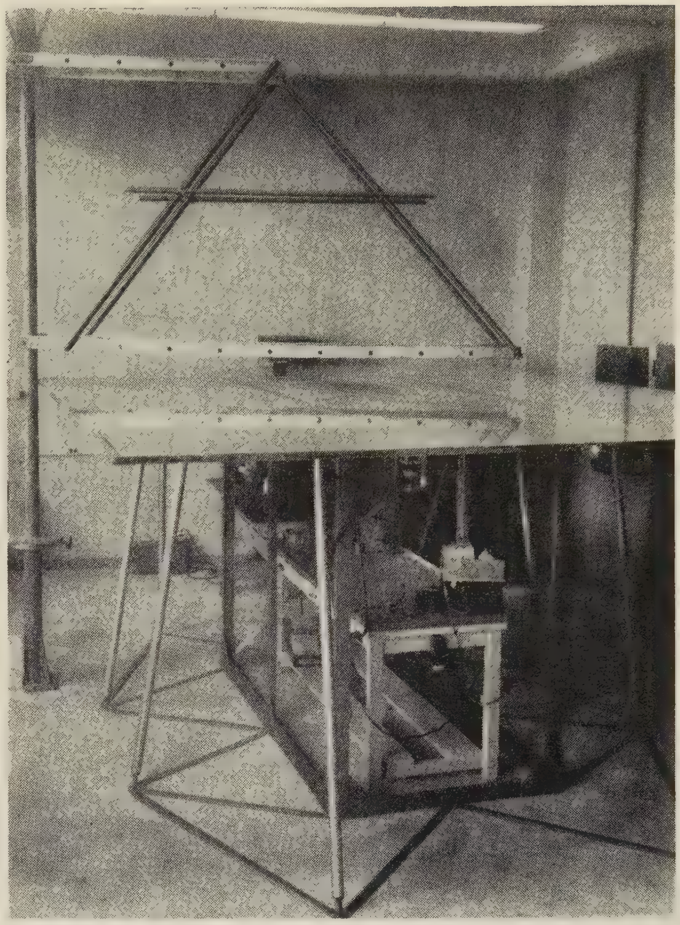

Fig. 2—Photograph of the scattering range.

The scattering range has been designed in such a way that back scattering can be measured as a function of aspect, and for a given aspect, the complete azimuthal pattern of the field can be measured. Studies have been made of families of spheres, cones, and spheroids, and many results have been presented already in reports and papers. Fig. 3 is illustrative of the type of study conducted and of the results which are obtained. The figure shows how the back scattering cross section, better known as the radar cross section in operational work, depends on the aspect presented by a cone to the incident wave. The major peaks in the pattern correspond to aspects for which specular reflection back to the source is possible. The secondary maxima are not due to specular reflection but to special combinations of the amplitude and phase relations in the induced current distribution over the cone. While the existence of maxima for aspects allowing specular reflection is easily predicted from theory, the other maxima are not. The cone is a surface which has singularities, discontinuities in the direction of the normal

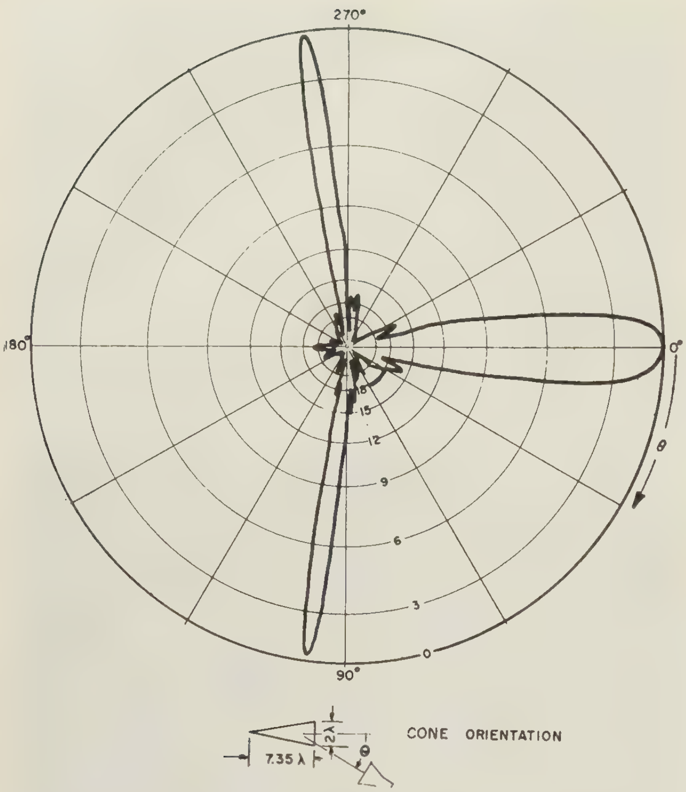

Fig. 3—Backscattering cross section of a cone as a function of aspect. 15° cone, 7.35 λ long, 2 λ base; $f = 9327$ mc.

to the surface. This feature, together with the fact that the base of the cone shown in the figure has a diameter comparable to the wavelengths, makes the application of usual approximations in the theoretical analysis questionable. The measurements enable the determination of the range of validity of known theoretical analyses. The practical significance of cones in space technology need hardly be noted, and the bearing of data such as shown in Fig. 3 on the problem of tracking a tumbling and rolling target is quite evident.

Currently studies are also being made of scattering by anisotropic bodies, for example, bodies of ferrites in magnetic fields. The work on ferrites is itself important to a basic understanding of the interaction between electromagnetic waves and media of that type. The instrumentation is being planned, however, to serve a larger purpose of studying the scattering of electromagnetic waves by plasmas. The results will further understanding of the structure and properties of confined plasmas, the applications of which range from development of thermocouples for generation of power to the possible employment of rocket exhausts as electromagnetic guides and radiators.

III. Circuit Analysis and Synthesis

A portion of the research in this field covers a variety of problems which have bearing on electronics for space vehicles. Work on microwave circuit elements utilizing the particular properties of ferrites provides data for the design of switching elements, phase shifters, and power dividers which are used in scanning antennas. Studies on basic communication of pulse data handling or processing circuits are directed towards determining optimum performance or limiting conditions of performance. Thus, for example, space vehicle requirements impose limitations on weight and size of electronic components and the objective is to achieve functions of amplification, oscillation and transmission by the minimum amount of circuitry compatible with the requirement of maintaining adequate levels of performance.

Naturally, transistors are given a large amount of attention. An important problem, for example, is the design of fast bistable transistor circuits (flip-flop circuits). It is known that high levels of performance can be achieved by using as many as nine transistors per flip-flop. There are conventional circuits which employ only two transistors per flip-flop, but it is commonly believed that such circuits are necessarily very limited in speed. Our work shows that this is not the case. Analysis and experimental investigation on flip-flop circuits have been carried out to determine the factors governing the performance of the circuit. The studies have led to a better understanding of the interrelationships among the elements of the circuit and to a knowledge of the factors limiting the performance and the optimum conditions for achieving fast speeds. The results have been verified experimentally and it has been found that properly designed "minimum-element" basic circuits perform almost as well as much more complex circuits.

As another example, mention may be made of the work being done on wideband or fast amplifiers. Here too there exist many misconceptions as to the best way of achieving wideband transistor amplifiers. The program in our laboratory has been to analyze and evaluate the many methods of achieving wideband characteristics and, subsequently, to develop optimum design techniques for the most promising types. It has been possible to establish classes of optimum amplifiers; it is thereby possible to determine quickly whether a given set of amplifier specifications are realizable with a given type of transistor. If so, a design can be established which minimizes the use of transistors and other components.

IV. Information Theory

The work in circuitry in its application to comunication circuits is of course greatly affected by the considerations arising from information theory and communication theory. Information theory is a relatively new field and, consequently, many of its basic concepts and theorems pertain to highly idealized situations. The relevance of these to actual situations could only be surmised. The work of our project, which is now in its second year, started with the objective of extending and developing the theory to more practical situations and of establishing the concepts and theorems for more practically meaningful situations.

The program is now entering into another phase. Studies are being conducted on coding, correlation and detection theory, and general systems analysis. A very important investigation is one involving both the information theory and propagation and radiation projects. It is the study of antennas from a data processing point of view. The problem can be formulated as follows: Given an antenna system composed of a number of antennas and considering the terminals of each antenna as an independently accessible pair, what correlation processes can be effected between the set of accessible terminal voltages (or currents) to derive the maximum data content available to the system? The monopulse radar, the Mills' cross-antenna used in radio-astronomy, and interferometers are effectively high resolution devices by virtue of a data processing technique rather than the "natural" beamwidth of the system. We are interested in determining the general principles which characterize and underlie all such antenna systems and thereby point the way to new designs. The application of the techniques to tracking, communications, and generally to space-radio relays needs no great elaboration. The need to conserve space within which antennas are to be placed, and at the same time to preserve resolution and freedom from ambiguities, seemingly can be met by data processing techniques. It remains to determine the extent to which that can be affected.

V. Solid State Electronics

Semiconductors are virtually the lifeblood of the instrumentation for satellites and other space vehicles, ranging in use from circuit elements to energy conversion devices. A better knowledge of the relation between the structure and physical properties of materials leads to improvement in the performance of known devices and points toward the invention of new ones.

Semiconductor devices in space vehicles may undergo very large changes in temperature, particularly when they are components of instrumentation installed in the surface of the vehicle. Studies are being made at this laboratory on the dependence of the properties of silicon carbide on temperature. Measurements of charge decay phenomena which follow the injection of a current pulse are directed toward elucidating the energy level structure of SiC. In parallel with the experimental work, theoretical investigations are being carried out on space charge phenomena in insulators and semiconductors. It is hoped that the results of this work will yield data on the basis of which semiconductors can be "designed" to have certain specified properties.

Selenium rectifiers and photocells are very important semiconductor devices. Attention is being directed toward obtaining a fundamental understanding of the material and the devices through a study of certain transient phenomena and their temperature dependence. The information which is being accumulated is of importance in considering the effects of temperature variations, sudden temperature changes, and long-term aging on the electrical characteristics of the material. Such effects must be given careful consideration in the interpretation of data obtained from space vehicles by means of instrumentation involving various types of selenium devices.

It has already been pointed out that there is interplay and exchange of ideas and techniques between the various projects. This is also true in the solid state electronics field. There are two studies being made in this area under the contract supporting the work on propagation and radiation. One has to do with ferromagnetic and parametric amplifiers in the microwave region, particularly the millimeter wave region. The two particular features or objectives of the study are 1) to accomplish the process using a pumping frequency lower than the signal frequency, and 2) to utilize a multimode cavity as the set of circuits required for such amplifiers. Even though a working amplifier may not be achieved, the study has thrown much light on the general problem and it is felt that much will have been learned which will be useful in further developmental work in these important components. Some amplification has actually been effected but it yet remains to be seen what is the ultimate performance that is possible.

A more recent study which has been initiated under the propagation and radiation project is that of the properties of organic semiconductors. There is a class of organic compounds, among which the commonly known are napthalene and anthracene, which are semiconductors when activated by light. The conductivity is a nonlinear function of the illuminating intensity and is also a function of the wavelength of the light. Of special interest are the characteristics exhibited by optically activated material in the microwave region. Such materials may have potentialities of being used in detection, switching, and amplification (or more generally, energy conversion). If that should prove to be the case, many applications to space technology can be envisaged. This work is really in its formative stages in our laboratory. Preliminary measurements have been made of Faraday rotation of microwaves in such materials, but the sensitivity of the measurement techniques which have been employed has proved to be much too low. Now we are engaged in an instrumentation program, out of which there will come, interestingly enough, a by-product in the form of a dielectrometer which may be useful in the form of a flush mounted system on rockets for measuring certain components of the atmosphere.

VI. Upper Atmosphere and Solar Investigations

Finally, there is an area of work which by designation as well as by substance is obviously related to a space research program. A study was started some time ago of microwave radiometers, and a radiotelescope was constructed for the 8.3 mm wavelength region. The particular choice of the band center was dictated by the then available data on absorption lines of ozone, with the thought that such a radiometer and telescope could then be used

to study the ozonosphere which is a layer of the atmosphere extending roughly from 25-60 km above the surface. Radio engineers have largely been concerned with the ionosphere and hardly at all with the ozone layer. However, the ozone layer plays an extremely important part in the heat exchange processes in the atmosphere and in maintaining the earth's temperature. It is a major factor in meterological phenomena.

The objectives of the project are many. Measurements of the ozone layer, or more precisely the total ozone content in the solid angle of the antenna beam, supplement the results obtained by studies in the optical and ultraviolet regions of the spectrum. In these measurements the sun is used as a source of millimeter radiation, and the investigations thus bring along with them data on solar activity. The small radiotelescope used to date is shown in Fig. 4. The beamwidth of this antenna is too broad to be able to separate activity of different parts of the sun. The Office of Naval Research has had made for this laboratory a paraboloidal reflector of a diameter of 10 feet whose surface tolerances are such that it can be used effectively to a wavelength of 4.5 mm. It is a duplicate of a reflector used by the Naval Research Laboratory. Work is now under way on the construction of the new radiotelescope and the mounting of it on the roof of Cory Hall. The beamwidth of the large antenna expected at 8.3 mm will be such that separate quadrants of the solar disc can be observed and studies of activity can be made with a higher degree of definition. The correlation between activity in the millimeter region and activity observed at longer wavelengths will be very useful in the analysis of the mechanism involved in the generation of the radiation. The new telescope will also be usable for observations of stars and nebulas which are known to give appreciable amounts of radiation in the longer wavelength regions of the spectrum. The spectral distribution of intensity is an important characteristic which must be known for the interpretation of stellar processes. The investigation also provides data on the noise background needed for the design and effective use of communication systems. Of no small significance is the measurement technique itself. The determination of the absorption associated with the ozone in the upper atmosphere is a measurement that lies at the threshold of radiometer sensitivity. Attention is being directed toward the general principles underlying the operation of radiometers and attempts are being made to devise new methods which will increase the sensitivity. The problems here fall into the domain of information theory and data processing antenna techniques which have been referred to earlier in this presentation. Any new results which will be obtained from this work will have very far-reaching effects in the development of antenna systems and communication techniques for space vehicles.

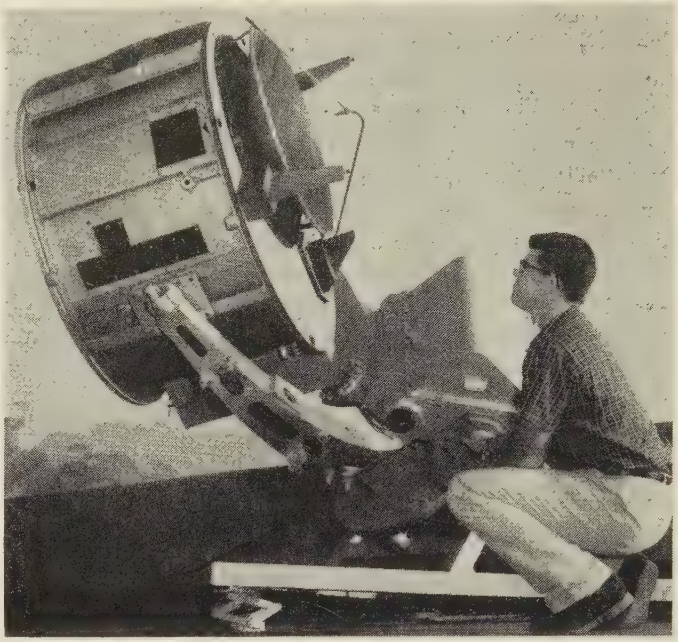

Fig. 4—8.3-millimeter radio telescope.

Communication Using Earth Satellites*

JEROME B. WIESNER†

Summary—**A review of the use of earth satellites for reliable, ionospheric-independent communication circuits includes considerations of losses in the propagating path, directivity features, and influences such as Doppler shift. The effects of such influences on bandwidth and range are illuminated.**

I. Introduction

THE possibility of employing earth satellites to carry radio repeaters offers a new means of providing reliable long-range communications. Such communication systems would not be subject to the vagaries of the currently employed short-wave radio circuits and, in addition, would be capable of transmitting much greater amounts of information than can be handled by the conventional systems. Satellite communication systems can be used for point-to-point radio relaying for military and civilian purposes and may ultimately be used to provide a world-wide radio and television service as well. The electronic components required for these applications are not beyond the present state of the art, though considerable development work is necessary to provide the specialized equipment suitable for this purpose. A number of systems having restricted, but useful, capacities could be tried within the next two years. Systems having greater capability but requiring the development of specialized radio and power equipment, satellites capable of carrying greater payloads, or both, are also feasible on a longer time scale.

Two types of relay satellites have been proposed; both are technically feasible. The first is the passive satellite, a large lightweight metalized sphere which is used to reflect radio signals emanating from a transmitter at one point on the earth's surface to a distant point beyond the line of sight from the transmitter.

The second scheme involves the use of active repeaters in the satellite. In this system, a radio receiver in the satellite intercepts the signal from a ground transmitter, amplifies it and then retransmits it to a receiver somewhere on the earth's surface. In one variation of the active system, the signals to be relayed are received as the satellite passes over the transmitting point, stored until the receiving site is within the range of the satellite, and then retransmitted. The passive satellite scheme has the advantage of simplicity of the airborne unit, and is avaliable, without interference, for use by anyone who can provide his own ground equipment. Because it has no active parts, it is highly reliable. Unfortunately, passive systems also have some disadvantages when compared with active relay systems. The transmission capacity of a passive relay is limited, as compared with possible active systems. The height at which the passive reflector may be placed in orbit to provide a useful communication circuit is restricted by signal-to-noise ratio limitations; consequently, the maximum range of a communication system using a single satellite reflection will be somewhat limited. Finally, a passive system requires the use of large tracking antennas and rather large transmitters, for which reasons it is not well suited for use as a mobile system. The need for very large receiving antennas also makes the use of a passive system unattractive for broadcast purposes.

II. Satellite Considerations

The factors of orbit characteristics and satellite payload affect the design of both passive and active relay systems. These factors will therefore be examined before we consider specific relay configurations.

The orbit characteristics are important because they determine the period of time for which a single satellite can be observed from a given point on the ground, and hence the transmission time that a given satellite will permit between two points. Consequently, the orbit characteristics will determine the number of satellites that are needed to provide continuous transmission between any two points. In the case of the delayed transmission system, the orbit characteristics will determine the anticipated time delays.

The period of an earth satellite is a function of the height. For a satellite in a circular orbit, the period of revolution is given by

$$T = \frac{2\pi R^{3/2}}{G \times r} \tag{1}$$

where R is the orbit radius measured from the center of the earth, r is the radius of the earth, and G is the gravitational constant at the earth's surface.[1] For very low orbits (of the order of 100 miles above the earth's surface), the period is in the order of 1.5 hours; at a height of 22,200 miles the orbit has a 24-hour period, which means that a satellite in an equatorial orbit could be made to remain stationary over a point on the earth's surface. While serious problems of orbital velocity control must be solved if such a satellite is to be employed, several schemes for accomplishing this control appear feasible.

Orbits are conveniently divided into two classes: the stationary or 24-hour equatorial orbit, and the low orbits

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[1] Many of the orbital data presented here are taken from W. E. Morrow, Signal Corps Barnstable Project, Massachusetts Institute of Technology, Cambridge, Mass.; 1958.

containing all nonstationary orbits regardless of orbit orientation. Generally, the low-orbit satellites will be employed at altitudes ranging from 1000 to 5000 miles above the surface of the earth.

A. Low Orbits

The orientation of the orbit with regard to the axis of the earth will be determined by the location of the points that the satellite relay is designed to link. For some purposes an equatorial orbit will be desirable; for others, a polar orbit—more accurately, a group of polar satellites if continuous communication is desired—may be advantageous. For example, Pierce and Kompfner[2] have chosen a polar orbit for a proposed relay link connecting the northern part of the United States with England.

There are a number of reasons for considering the use of satellites in low, nonequatorial orbits for communication purposes.

The stationary orbit requires a satellite at very high altitude (in excess of 22,000 miles). As we shall see, it is difficult and costly to design an adequate passive relay system with reflectors at so great a height; this distance may even be too great for some active satellite systems. Second, the 24-hour equatorial satellite cannot be seen within 8° of either pole, which eliminates the possibility of using it for communication with the Arctic or Anarctic regions. Finally, the low-altitude satellite may offer greater security from jamming than does the stationary satellite.

In order to provide continuous communication between two points on the earth's surface (whose antennas can see some part of the trajectory of a low satellite), a number of satellites will be needed. The exact number will depend upon the geometry of the situation and the station-keeping ability of the individual satellites. For a satellite at height R, the fraction of the earth's surface over which a satellite is visible at one time is given by[1]

$$p = \frac{1.28}{2\pi}\left[\cos^{-1}\frac{r}{R\cos L/2R}\right] \cdot \left[\frac{\pi}{2} - \frac{L}{2r} - \sin^{-1}\frac{r}{R}\right] \qquad (2)$$

where R and r have the same meaning as before, and L is the distance between the two sites. Fig. 1 is a plot of (2) for various heights and distances between sites.

From (2) it is possible to calculate the number of satellites in a circular orbit that will be required to provide communication for a given fraction of the time over a specified path of length L. The quantity p is the probability that a given satellite is visible to the two sites desiring to communicate. Thus $P = (1 - p)^n$ gives the probability that of

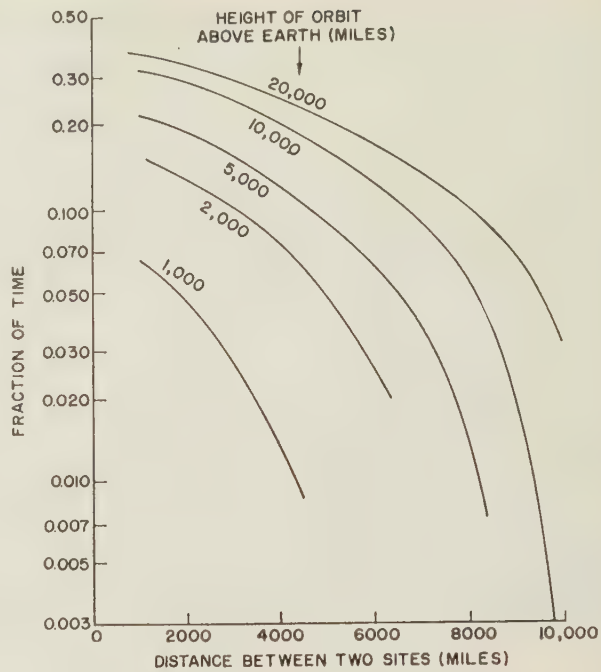


Fig. 1—Fraction of time that a satellite at a given height will provide service between two sites. (From Morrow.[1])

n satellites in random orbits, none will be visible simultaneously from the two sites. Because of the statistical nature of the arrival of a satellite in the common volume between the transmitter and the receiver, a large number of satellites will be required to insure a high probability of having one satellite in this volume.

However, if the orbital position of each satellite is appropriately planned and the period of the individual satellites is made the same so that they arrive uniformly spaced in time, a smaller number of satellites will provide essentially continuous service. In fact, approximately $n = \frac{1}{p}$ of them will then be adequate. The curves of Fig. 2 show the number of satellites in random orbits required to provide a 99.9 per cent reliable circuit. Also shown are the number of satellites in synchronized orbits required to provide essentially continuous communication. It may be seen that a heavy penalty is paid for the inability to control the satellites in their orbits.

B. 24-Hour Orbit

The 24-hour satellite revolving in an equatorial plane is particularly attractive because it effectively hovers over a given point on the earth's surface, thus providing continuous coverage between any pair of points on the earth's surface from which it is simultaneously visible. Three such satellites would provide world-wide coverage (excluding the polar regions previously discussed). A single stationary satellite would suffice to span the Atlantic Ocean, a second could span the Pacific. We shall see later that it is within the present state of the art to build a repeater for such a satellite which would have sufficient channel capacity to provide an effective world-wide communication system.

[2] J. R. Pierce and R. Kompfner, "Transoceanic communication by means of satellites," Proc. IRE, vol. 47, pp. 372-380; March, 1959.

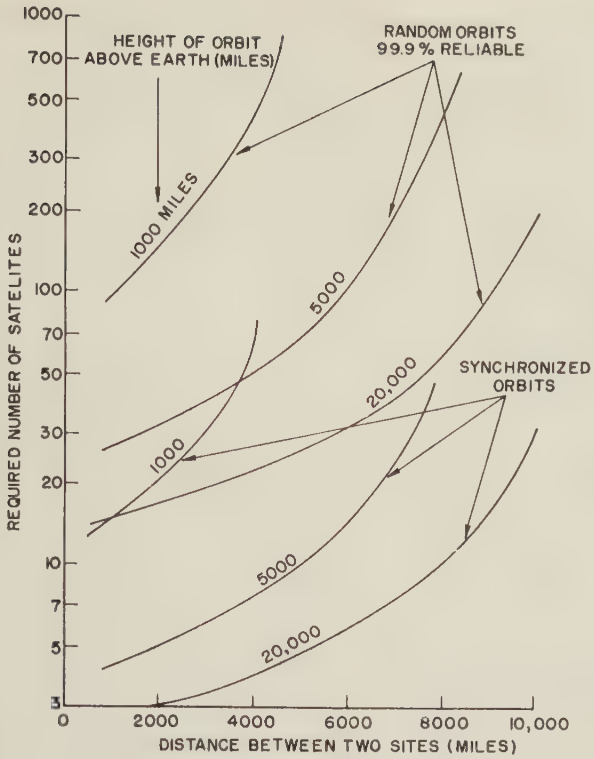


Fig. 2—Number of satellites required for synchronized and random orbits. (From Morrow.[1])

III. Factors Affecting System Performance

A. Passive Relay Systems

In the passive system, a metalized balloon placed in orbit is used to reflect energy from a ground-based transmitter to a receiving station. Only a very small fraction of the initial radiated energy is intercepted by the sphere, and only a portion of the energy reflected by it is in the direction of the receiving station; consequently, a passive system requires large antennas and large transmitters.

The signal-to-noise ratio of a passive relay system is given by

$$\frac{S}{N} = \frac{P_t G_t A_R k^2 \sigma}{(4\pi)^2 R_1^2 R_2^2 (KTB)} \tag{3}$$

where P_t is the transmitted power;

KTB is the effective receiver noise power in a bandwidth B at temperature T;
G_t is the gain of the transmitting antenna;
σ is the scattering cross section of the passive satellite;
R_1 is the distance from transmitter to satellite;
R_2 is the distance from satellite to the receiver;
k is a factor that accounts for atmospheric absorption of the radiowaves each way.

This result will be compared with that obtained for a satellite communication system employing an active repeater.

B. Active Relay Systems

In active systems, the signal to be relayed is received and rebroadcast by the equipment in the satellite. In this situation, two relay circuits are actually operated in cascade. The first is a circuit consisting of a ground transmitter and its antenna system which beams a signal to be received by the satellite; the second channel consists of the satellite-borne transmitter and its antenna which radiates with a ground antenna-receiver system. Because of power supply limitations in the satellite, the latter circuit normally will limit the capacity of satellite relay systems and is the only circuit which we need to investigate. Accordingly, the S/N ratio of an active relay will be

$$\frac{S}{N} = \frac{P_{ts} G_{ts} A_R k}{4\pi R_2^2 (KTB)} \tag{4}$$

where P_{ts} is the power output of the satellite transmitter;

G_{ts} is the gain of the satellite antenna;
A_R is the receiving cross section of the ground antenna;
KTB is the effective receiver noise power in a bandwidth B at a temperature T;
R_2 is the distance from the satellite to the ground receiver;
k is a factor that accounts for atmospheric absorption of the radio waves.

C. Comparison of Active and Passive Relay Systems

Since an active relay is probably more difficult to build and to place in a proper orbit, it should have clear-cut advantages if it is to be chosen in preference to a passive reflector. Assuming that the active satellite and the passive reflector are at the same height and the same distance from the receiver and that the same receiver and the same frequency are used in both cases, the performance of the active system relative to the passive one will be

$$\frac{S_{\text{act}}}{S_{\text{pas}}} = \frac{4\pi P_{ts} G_{ts} R_1^2}{P_t G_t k \sigma} = \frac{4\pi P_{ts} A_{ts} R_1^2}{P_t A_t k \sigma}. \tag{5}$$

If we assume a stationary orbit and the following reasonable values for the factors in (5):

$P_{ts} = 1$ watt,
$A_{ts} = 1$ square meter,
$R_1 = 24{,}000$ miles,
$P_t = 10{,}000$ watts,
$A_t = 100$ square meters,
$\sigma = 100$ square meters, and
$k = 1$,

we find that

$$\frac{S_{\text{act}}}{S_{\text{pas}}} = 1.85 \times 10^8. \tag{6}$$

This comparison will be considered unfair by some people because satellites in a 24-hour orbit were compared. While it is true that the comparison would not have appeared so unfavorable if a lower orbit had been examined, there are reasons that make low orbits not as desirable as a stationary orbit.

For an active system, the signal-to-noise ratio in a 1-mc bandwidth will be [from (4)] 26 db if $G_{ts} = 1$, $T = 30°K$, and $A_R = 3000$ square meters. This is sufficient circuit capacity for a substantial number of telephone or telegraph circuits. Obviously, the available power may be disposed of in other ways to give circuits with different bandwidths and other signal-to-noise ratios. The significant thing is that one watt of power radiated from a satellite is adequate to provide a very large amount of circuit capacity. In this example, the satellite antenna was assumed to have unity gain. If vertical stabilization can be achieved on the satellite, and this does not appear to be difficult, an antenna having approximately 20 db of gain can be employed on the satellite and still provide world-wide coverage. This would permit a circuit bandwidth of 100 mc with the same signal-to-noise ratio as was achieved in the unity gain example.

D. Factors Affecting the Choice of Operating Frequency

The choice of operating frequency is affected by a large variety of considerations. Among the most important considerations are the availability of components, the availability of adequate spectrum space for the service proposed, the sky noise which the ground receivers will intercept, and the primary power available in the satellite for operating the communication relay equipment. These items will be examined in the following sections.

1) Primary Power Sources: The power available in the satellite for operating the relay equipment and the stabilization equipment sets the upper limit on the equipment that can be considered. In the near future—the next two to four years—the best source of power in the satellite for a continuous duty service will be solar cells used in conjunction with a storage battery to supply energy when the satellite is in the earth's shadow. At the present time, solar cell-storage battery combinations weigh approximately four pounds per watt of available power. Since the rockets available now can only lift a few hundred pounds into a 22,000-mile orbit, the total available power for relay operation will be limited to about 100 watts. Within a decade, it should be possible to put many tons into a stationary orbit, and then the available primary power will not be a serious limitation on the design of these systems.

Other sources of power are being developed for satellite use. Among these are nuclear-powered units and solar engines that use solar energy in the form of heat. When larger satellites become available, such energy sources will doubtless be used.

2) Radio-Frequency Power Sources: Because of the limited amount of primary power available at the present time, the choice of transmitting devices for use in a satellite relay is severely limited. The scarcity of energy puts a premium on transmitter efficiency in relation to other factors and limits the total capacity of the relay system. The following devices appear to have some merit for use in relay systems.

a) Transistors: Transistors having a power output of approximately 1/4 watt at frequencies up to 400-500 mc are now available. By using several of them in parallel, a watt or two of power could be obtained. This performance is probable up to frequencies in the neighborhood of 1000 mc.

The transistor has the advantage of very high reliability and good efficiency. Unfortunately, there does not appear to be any reasonable hope of greatly increasing (in the near future) the power obtainable in the frequency range now achievable, or of substantially increasing the frequency at which transistors can be made to operate.

b) Triodes: Close-spaced triodes of the 416B, 2C39 types can be used to provide power outputs in the 1-watt range. Below 1000 mc, as much as 1000 watts can be obtained from tubes of this general design.

Properly designed triode amplifiers can have good efficiencies at these frequencies.

If triode amplifiers are to be used in satellite applications, considerable care will have to be taken to provide proper cooling for the tubes or inadequate life will result.

c) Beam tubes: Klystron amplifiers and traveling-wave tubes are the most promising for use at frequencies higher than approximately 2000 mc and for power outputs in excess of a few watts.

Unfortunately, both the klystron amplifier and the traveling-wave tube are less efficient at low power levels than they are at high power levels.

It should be possible to make power amplifiers using beam tubes in the range from 1 watt to several hundred watts and with power gains of the order of 30 db at any frequency up to about 10,000 mc. At low power levels, it may be difficult to obtain bandwidths that are adequate for communication purposes (*i.e.*, > 1 mc).

3) Low-Noise Receivers: The capacity of a radio-relay link is determined by the signal-to-noise ratio present at the output of the receiver. This, in turn, is determined by the total received signal power and the noise present at the output of the receiver. The received power, as we have already seen, is determined by the transmitter power, the transmitting and receiving antennas and the path geometry. Eqs. (3) and (4) also indicate that the signal-to-noise ratio varies inversely as the noise temperature T of the receiver. The temperature T of the receiver corresponds to the actual temperature of a resistor whose value equals the output resistance of the receiver and which is capable of transferring the same noise power to a resistive load as would the actual receiver.

The noise output from the receiver originates from two principal components: the shot noise associated with the electron flow in the tubes and the external noise contributed by various sources, of which the antenna noise and the sky noise are the most important.

Until quite recently, the shot-noise contribution from the tubes was so large that it completely masked the external noise. Typical noise temperatures for amplifiers ranged from 600°K at 200 mc to 3000°K at 10,000 mc. Two new UHF developments have completely altered this situation: parametric amplifiers[3] and masers[4] can be made so quiet that noise from the "sky" is now often the limiting factor in determining receiver performance.

Parametric amplifiers having noise temperatures of less than 100°K can be operated at a few hundred megacycles. Comparable performance can be achieved up to frequencies in the neighborhood of 3000 mc. There is good reason to expect that similar performance can be obtained at very much higher freqencies.

Maser amplifiers can be made with noise temperatures in the range of 10° to 30°K over the frequency range of interest for satellite communication.

It is fortunate that the ground-to-satellite link is not power-limited, and that this makes ultimate receiver performance required only on the satellite-to-ground section of the link.

4) Background Noise: The important sources of noise that must be taken into account in choosing the operating frequency for a satellite communication system are cosmic noise from space, thermal noise associated with atmospheric absorption, and noise from the sun.

Cosmic noise is strongest in the direction of the galactic center of our Milky Way. Fig. 3 shows the manner in which the cosmic background noise varies in different positions of the sky. Fig. 3 is drawn for 250 mc. Measurements indicate that the cosmic noise decreases with increasing frequency. Fig. 4 shows the variation of cosmic noise intensity as a function of frequency.

The absorption of microwave energy by constituents of the atmosphere implies a mutual coupling between these elements, principally oxygen and water vapor, and the receiving antenna. The exact effect of atmospheric absorption depends upon the direction of the signal from the earth, a ray departing along the horizon being most affected. The curves of Fig. 5 show the absorption as a function of frequency for one set of conditions. By assuming a temperature for the atmospheric constituents, the noise which this effect will introduce into the receiver can be calculated. In general, it is well to stay below 10,000 mc if ultrasensitive receivers are to be employed. Even at this frequency, serious absorption may be encountered during heavy rains.

[3] A. Uhlir, "The potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, pp. 1099-1115; June, 1958.

[4] G. Makhov, C. K. Kuchi, J. Lambe, and R. Terhune, "Maser action in ruby," *Phys. Rev.*, vol. 109, pp. 1399-1400; February 15, 1958.

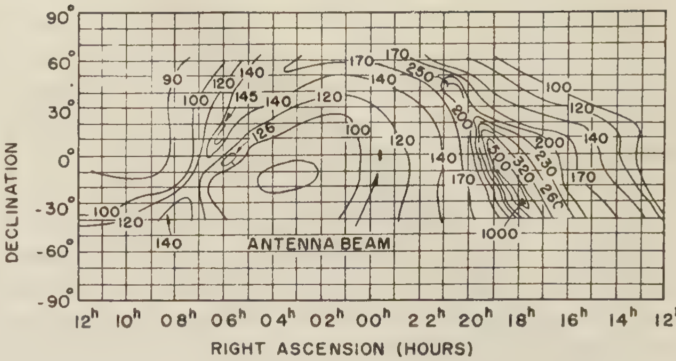


Fig. 3—Map of the radio sky background at 250 mc. (After Ko and Kraus.) The contours give the absolute brightness temperature of the radio sky in degrees Kelvin.

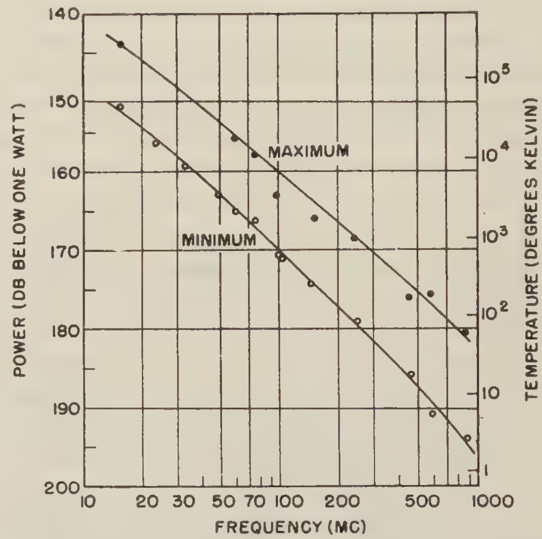


Fig. 4—Maximum and minimum cosmic noise as a function of frequency at 1-kc bandwidth.

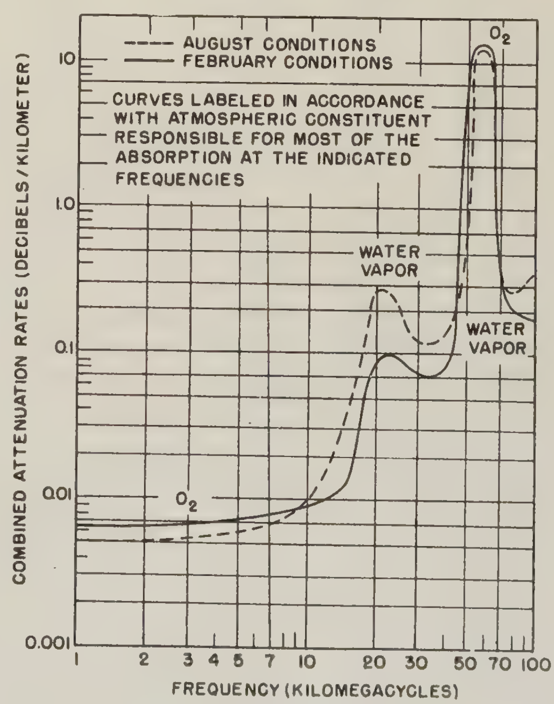


Fig. 5—Combined attenuation rates due to oxygen plus water vapor at surface.

The sun is a prolific source of radio noise. In general, it is best to design the satellite system to avoid direct intercept of the sun by the receiving beam. During those infrequent periods when this cannot be done, serious degradation of the system will be experienced.

IV. Typical Systems

Several examples of active relay systems will now be worked out to illustrate a variety of applications and to show the performance that might be expected as the systems evolve. The properties of these systems are shown on Table I.

A. Point-to-Point Relay

1) Low-Power, Lightweight: It would be possible within a time period of approximately one year to establish an experimental low-power active satellite relay system. Such a unit having a power output in the range of one watt could be made to have a total weight of 50 to 100 pounds. Launching vehicles for such a payload will be available during this period. If the ground receiving system used a 60-foot antenna, and the satellite was at a height of 2500 miles, the system would have a signal-to-noise ratio of approximately 25 db and an intelligence bandwidth of 4 mc, enough for simultaneous telephone and television transmission.

Characteristics of this system are given in column 3 of Table I. The frequency and power levels of this system were chosen so that it would be feasible to build the airborne equipment now using existing transistors and solar-cell power supply. Column 4 shows the performance of the same airborne relay when used in conjunction with a 10-square-foot receiving antenna, such as might be available on a ship. The 10-kc bandwidth available would be entirely adequate for ship-to-shore communication. It is possible that it could be used with even smaller receiving antennas for communication with aircraft.

Columns 5 and 6 show the performance which could be achieved with this low-power relay in a 24-hour orbit. If we use a receiving antenna having a 60-foot diameter, an intelligence bandwidth of 100 kc can be achieved. This is entirely adequate for many communication purposes. With a 250-foot-diameter receiving antenna, a 2-mc bandwidth could be achieved which is capable of relaying a signal with approximately the same signal-to-noise ratio as in the previous case.

TABLE I
Satellite Communication Systems

Power Aloft		Non-Passive 100-Foot-Diameter Balloon		Low-Power—1 Watt				Medium-Power—100 Watts				
1	Function	Point-to-point relay 1	Point-to-point relay 2	Point-to-point relay 3	Fixed point to mobile 4	Point-to-point relay 5	Point-to-point relay 6	Point-to-point relay 7	Fixed point to mobile 8	Fixed point to mobile 9	Point-to-point relay 10	FM broad-cast 11
2	Orbit	Polar	Equatorial	Polar	Polar	Equatorial	Equatorial	Polar	Polar	Equatorial	Equatorial	Equatorial
3	Orbit Height	2500 miles	22,000 miles	2500 miles	2500 miles	22,000 miles	22,000 miles	2500 miles	2500 miles	22,000 miles	22,000 miles	22,000 miles
4	Period	3 hours	24 hours	3 hours	3 hours	24 hours	24 hours	3 hours	3 hours	24 hours	24 hours	24 hours
5	Fraction of Time Available	0.15	1.0	~0.15	~0.15	1.0	1.0	~0.15	~0.15	1.0	1.0	1.0
6	Weight of Satellite	200 pounds	200 pounds	50–100 pounds	50–100 pounds	50–100 pounds	50–100 pounds	~1000 pounds	~1000 pounds	1000 pounds	1000 pounds	1000 pounds
7	Bandwidth	4 mc	1.0 kc	4 mc	10 kc	100 kc	1.7 mc	~100 mc	400 kc	10 kc	8 mc	250 kc
8	Signal-to-Noise Ratio	20 db	20 db	24 db	20 db	24 db	24 db	24 db	20 db	20 db	24 db	24 db
9	Frequency	2000 mc	2000 mc	400 mc	400 mc	400 mc	400 mc	400–2000 mc	400–2000 mc	400–2000 mc	400–2000 mc	100 mc
10	Ground Transmitting Antenna	250-foot diameter	250-foot diameter	28-foot diameter	28-foot diameter	28-foot diameter	28-foot diameter	28-foot diameter	28-foot diameter	28-foot diameter	60-foot diameter	60-foot diameter
11	Ground Transmitting Power	10,000 watts	10,000 watts	100 watts	100 watts	500 watts	3000 watts	100 watts	100 watts	~500 watts	500 to 1000 watts	1000 watts
12	Ground Receiving Antenna	250-foot diameter	250-foot diameter	60-foot diameter	10 square feet	60-foot diameter	250-foot diameter	28-foot diameter	4 square feet	4 square feet	60-foot diameter	10 square feet
13	Ground Receiving Noise Temperature	30°K	30°K	100°K	300°K	100°K	100°K	100°K	300°K	300°K	100°K	600°K
14	Number of Satellites for 99 Per Cent Availability	10–20	1	10–20	10–20	1	1	10–20	10–20	1	1	1
15	Availability of Experimental Model	1–2 years	1–2 years	1–2 years	1–2 years	1–2 years	1–2 years	2–4 years	2–4 years	2–4 years	3–5 years	3–5 years

Note: Isotropic antenna on satellite except for broadcast where $G_1 = 20$ db.

For comparison, column 2 shows the performance that could be achieved with a passive system if the satellite were placed in a 24-hour orbit at a height of approximately 22,000 miles. The bandwidth available in this case is so narrow that the system is not likely to be very useful.

If the distance between transmitting and receiving sites were 3000 miles in the case of the low-altitude satellite, approximately 10 such satellites would be required to provide a continuous service. The number required increases as the ground spacing is increased. Approximately 20 such satellites would be required if the distance between the sites were increased to 5000 miles. The number of balloons required could be reduced by increasing the height of the orbit, but unfortunately the strength of the signal falls off rapidly as the height is increased.

If continuous service is not required, a small number of satellites might give adequate service. For the 3000-mile path examined, if we assume a balloon satellite at a height of 2500 miles, a single sphere in the proper orbit would provide a circuit for approximately 15 per cent of the time.

The passive satellite has one very attractive property: it is available to anyone who chooses to use it, and the only precaution which needs to be taken to avoid interference between different users is proper allocation of operational frequencies. Such a balloon is not frequency-sensitive, so a wide range of frequencies is available for this application. Active systems will probably not be able to operate over nearly as wide a frequency band. In addition, they must be used with care if they relay more than one signal, in order to avoid interchannel interference.

Designs exist for the balloons, and they will shortly be tested by NASA. Transmitters and antennas for this purpose are available, and it is probable that an experimental passive relay link could be made operational within one year.

The spherical reflector appears to be the most satisfactory shape for a passive reflector. Various proposals for flat surfaces, corrugated surfaces, and specialized shapes have been made, but on critical examination they are found to have disadvantages when compared with the spherical balloon.

2) Medium-Power: As satellites capable of carrying larger payloads become available, the performance of the active relay systems can be substantially improved. For example, if the power output of the satellite relay transmitter discussed in the previous section were increased to 100 watts, the system performance would be improved by 20 db. This improvement is particularly needed to make the mobile system fully effective. The performances of several such systems are given in columns 7–10. With the power supplies available now, a 100-watt satellite would weigh approximately 1000 pounds. Most of this weight would be in the power system, so that improvements in power supply, particularly in the energy-storage-per-unit weight of storage batteries, would reduce the total satellite weight considerably.

A satisfactory transmitter tube for this application does not exist, although a tube having requisite efficiency and life expectancy does not appear to be beyond the state of the art.

3) Storage and Rebroadcast Systems: A system using storage equipment in a satellite has been proposed to extend the transmission range of a single satellite. Such a system would probably employ an equatorial orbit at a height of 1000 to 2000 miles and can be used in conjunction with a ground system similar to those discussed previously. The satellite would receive messages as it was passing over the sending station, store them on a magnetic tape memory, and retransmit the messages as it passed over the receiving site. This process would involve delays of the order of 30 minutes to an hour depending on the location of the transmitting and receiving sites and the height of the orbit. For many purposes, such delays would not be serious. Unfortunately for foreseeable storage systems, the information capacity of this system would be limited.

B. Broadcast Service

One of the most exciting advances made possible by the development of satellites is the possibility of establishing a world-wide broadcasting system in the standard frequency-modulation band with the employment of only a few medium-power transmitters. Column 11 shows the performance that would be obtained with a 100-watt transmitter in equatorial orbit. The signal on the surface of the earth is sufficiently strong that it would afford high-quality reception over most of the hemisphere illuminated by the satellite, even when only a modest outdoor receiving antenna is used on the ground. In fact, the signal is sufficiently strong that one might be tempted to provide this service with a lower-power satellite relay, as for example, one radiating only 10 watts instead of 100 watts. Such a system would probably give marginal performance under many conditions. In the example chosen, the standard 100-mc FM band was employed so that existing FM receivers would be able to receive programs from the satellite relay. If desired, the relay system could be equipped to provide subcarrier audio channels when voice messages are being broadcast in order to provide the capability of broadcasting in several languages simultaneously. In this case, special receivers would be required having the necessary selector circuitry to enable the listener to select the language of his choice.

The system whose characteristics are given in column 11 is not quite adequate for television broadcasting. A minimum of 10 db better performance would be required for this purpose. This could be achieved by using a 1000-watt transmitter in the satellite or by employing a better receiving system. One thousand watts of radiated power would require a satellite system (including power supply) that is well beyond the present state of the art. The improvements in receivers and antenna systems, while within

the present state of the art, would probably make the individual television receiver too expensive for widespread use.

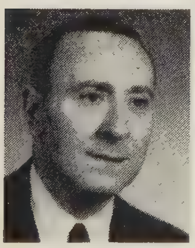
V. Economic Considerations

Any estimate of the cost of creating and operating a satellite communication system will obviously be highly conjectural at this time. By far the most expensive item required for a satellite communication system is the large rocket required to lift the relay system into an orbit far above the surface of the earth. At the present time such rockets cost approximately $5,000,000 apiece. In addition, until the reliability of large rockets improves, one must count on failures which may greatly increase the cost of building a system.

Assuming that a satellite relay can be built and put into orbit for $15,000,000 and that the associated ground equipment costs another $5,000,000 for connecting two points on the surface of the earth, the total cost of the relay system will be $20,000,000. A circuit bandwidth of 100 mc can readily be achieved so that the initial cost of the circuit will be of the order of $200,000 per megacycle. Further, assuming that a satellite will have a five-year life, the equipment cost amounts to approximately $40,000 per year per megacycle. Compared to this sum, the operating cost will be insignificant.

The circuit cost is independent of distance for all distances within the line of sight of a single satellite; that is, for distances up to approximately 8000 miles. From these data, it may be seen that even for relatively short circuits, the cost of a satellite relay system will be competitive with other means of relaying wide-band information.

Contributors



M. Arditi

Maurice Arditi (SM'46) was born on March 1, 1913, in Paris, France. He graduated from the Ecole Superieure Physique et Chimie, Paris, in 1935 and from the Ecole Superieure Electricite, Paris, in 1936 and received the M.A. degree in physics in 1939 and the Ph.D. in physics in 1958, both from the Sorbonne, Paris.

He has been associated with the ITT system since 1939, first with the Laboratorie Central de Telecommunications in Paris, and, since 1944, with the ITT Laboratories in Nutley, N.J. He has been engaged in research and development in electron devices and microwave components, and, since 1956, has been active in the development of a gas cell atomic clock.

Mr. Arditi is a member of the New York Academy of Sciences.

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K. J. Craig

Kalen J. Craig was born in Larned, Kan., on March 29, 1921. He is studying electrical engineering at George Washington University, Washington, D.C.

From 1942 to 1946, he served in the U. S. Marine Corps, and graduated from the Radio Materiel School of the U. S. Naval Research Laboratory; he also acquired experience with naval radar equipment and radio-controlled aircraft. He joined the Wave Propagation Branch of the Naval Research Laboratory, Washington, D.C., in 1952 and engaged in the study of electromagnetic propagation in the troposphere.

Since Mr. Craig became affiliated with the Radio Astronomy Branch of NRL early in 1957, he has worked on the moon radar project.

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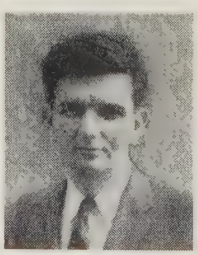

R. H. Dicke

Robert H. Dicke was born in St. Louis, Mo., on May 6, 1916. He received an A.B. degree in physics from Princeton University, Princeton, N.J., in 1939 and the Ph.D. degree in physics from the University of Rochester, Rochester, N.Y., in 1941.

From 1941 to 1946 he was a staff member of the Radiation Laboratory at the Massachusetts Institute of Technology, Cambridge. Since 1946 he has been a faculty member of Princeton University.

Dr. Dicke is a member of the American Physical Society.

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W. P. Dyke

Walter P. Dyke (M'56) was born on December 9, 1914 in Forest Grove, Ore. He received the B.A. degree in physics from Linfield College, McMinnville, Ore., in 1938. From 1942 to 1945 he was a staff member of the Radiation Laboratory at Massachusetts Institute of Technology, Cambridge, Mass., and he received the Ph.D. degree in physics from the University of Washington in 1946.

From 1946 to 1955, he was associated with Linfield College as professor of physics and head of the Physics Department, and as director of research. He became director of the Linfield Research Institute in 1955. His research and published work has been done in the area of electron physics, particularly field emission and associated phenomena. In 1946, he was awarded the Presidential Certificate of Merit, and in 1958 he received both the Electronic Achievement Award, Region Seven, IRE, and a citation from the Oregon Academy of Science.

Dr. Dyke is a member of the American Physical Society, the Oregon Academy of Science, the American Association of Physics Teachers, Sigma Xi, and Phi Sigma Phi.

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H. Friedman

Herbert Friedman was born on June 21, 1916, in New York, N.Y. He received the B.A. degree from Brooklyn College, Brooklyn, N.Y., in 1936, and the Ph.D. degree from The Johns Hopkins University, Baltimore, Md., in 1940.

After a year as an instructor in physics at Johns Hopkins, he joined the staff of the Metallurgy Division of the Naval Research Laboratory, Washington, D.C., and has been with NRL to the present. In 1942 he became head of the Electron Optics Branch and in 1958 was appointed Superintendent of the Atmosphere and Astrophysics Division. Since 1949, he has been engaged in upper air research with rockets, particularly in the field of solar-terrestrial relationships. He is currently involved in the instrumentation of U. S. satellites and serves as a member of the Working Group on Internal Instrumentation of the U. S. Technical Panel on the Earth Satellite Program.

Dr. Friedman received the Navy Distinguished Civilian Service Award in 1946 and the Annual Award of the Society for Applied Spectroscopy in 1957. In May, 1959 he received the Department of Defense Distinguished Civilian Service Award. He is a Fellow of the American Physical Society, a Fellow of the American Rocket Society, a member of the Committee on Astronomy and Radio Astronomy of the Space Science Board, Chairman of the Committee on Instrumentation and Controls of the American Rocket Society, a member of the Committee on Cosmic Terrestrial Relations of the American Geophysical Union, and a member of the American Optical Society, and of the Washington Academy of Sciences.

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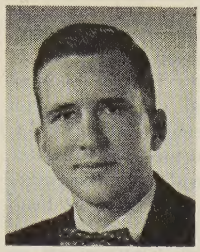
W. F. Hoffmann

William F. Hoffmann was born in Manchester, New Hampshire, on February 26, 1933. He received a Bachelor of Arts degree in physics from Bowdoin College in Brunswick, Maine, in 1954.

Since 1954 Mr. Hoffmann has been a graduate student and instructor of physics at Princeton University, Princeton, New Jersey.



H. R. Johnson

H. Richard Johnson (S'45–A'51–SM'55) was born on April 26, 1926 in Jersey City, N.J. He received the B.E.E. degree with distinction from Cornell University, Ithaca, N.Y., in 1946. Dr. Johnson studied at the Massachusetts Institute of Technology, Cambridge, under a Research Laboratory of Electronics Fellowship. His major studies there were in the fields of quantum mechanics and electromagnetic theory. He also worked on the microwave absorption spectrum of ketene, on an ammonia beam spectroscope, and on wave propagation on a helix. He received the Ph.D. degree in physics from the Massachusetts Institute of Technology in 1952.

From 1952 through 1957, he was with the Research Laboratories of the Hughes Aircraft Company, Culver City, Calif., where he was head of the Microwave Tube Department. Here he performed research and development work in the fields of high-power traveling-wave tubes, backward-wave oscillators, and traveling-wave tube oscillators and mixers. He was also a lecturer in engineering at the University of California, Los Angeles. He is presently vice president of Watkins-Johnson Company, Palo Alto, Calif., and lecturer in electrical engineering at Stanford University, Stanford, Calif.

Dr. Johnson is a member of the American Physical Society, past chairman of the Los Angeles IRE Professional Group on Electron Devices, and a member of Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi, Sigma Xi, and RESA.

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R. Krotkov

Robert Krotkov was born in Toronto, Can., on July 17, 1929. He attended Queens University in Kingston, Can., and received the B.A. degree in physics in 1951. His subsequent graduate work in physics was done at Princeton University, Princeton, N.J., where he received the Ph.D. degree in 1958.

Since then he has been engaged in research on gravitation with Prof. Dicke's group at Princeton.

Dr. Krotkov is a member of the American Physical Society.

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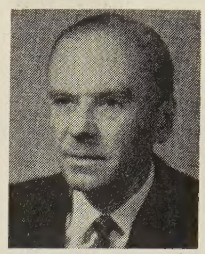

G. C. McVittie

George C. McVittie was born in Izmir, Turkey, on June 5, 1904. He attended the University of Edinburgh from 1923-28, during which time he received the Bruce of Grangehill Entrance Scholarship and the Charles McClaren Scholarship, was Newton Bursar, and received the M.A. degree with First Class honors, in mathematics and natural philosophy; in 1927, he held the Nichol Foundation in Natural Philosophy. He did his doctoral studies at Cambridge University, receiving his degree in 1930.

Dr. McVittie has held a number of University posts. These have included: assistant lecturer, Leeds University, 1930–1933; lecturer, University of Edinburgh, 1933–1934; lecturer in applied mathematics, University of Liverpool, 1934–1936; reader in mathematics, King's College, University of London, 1936–1948; professor of mathematics, Queen Mary College, University of London, 1948–1952; professor of astronomy and head of department, University of Illinois, Urbana, 1952 to present.

Concurrent with his university work, were positions as joint editor of *The Observatory* 1938–1948, and of the *Quarterly Journal of Mechanics and Applied Mathematics,* 1947–1951. During World War II, he served with the Meteorological Office of the Air Ministry and a department of the Foreign Office. During the four years prior to his coming to the United States, he served on the Meteorological Research Committee.

Dr. McVittie, an officer of the O.B.E., is a Fellow of the Royal Society of Edinburgh and of the Royal Astronomical Society. His memberships also include the International Astronomical Union and the American Astronomical Society.

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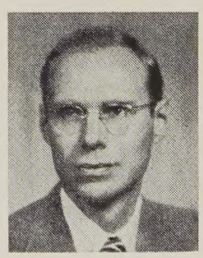


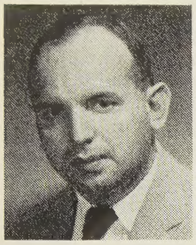
J. R. Pierce

John R. Pierce (S'35–A'38–SM'46–F'48) was born in Des Moines, Iowa, on March 27, 1910. He received the B.S. degree in 1933 and the Ph.D. degree in 1936 from the California Institute of Technology, Pasadena, Calif., and came to the Bell Telephone Laboratories the same year.

From 1936 to 1955 he worked on high-frequency electron tubes, and particularly on traveling-wave tubes. He is now Director of Research—Communications Principles, a field including research in radio, electronics, acoustics and vision, mathematics, and group behavior.

He is a Fellow of the American Physical Society, and the Acoustical Society of America, and a member of the National Academy of Sciences and of the British Interplanetary Society.

Allan Shapiro was born in Vienna, Austria on May 22, 1922. He received the B.E.E. degree from City College of New York, N.Y., in 1948.



A. Shapiro

From 1943 to 1946 he served in the United States Army, and worked on the development of microwave relay stations. In 1948 he joined the Instrumentation Branch of NACA, Langley AFB and was engaged in the development of telemetering components for missiles. In 1951 he joined the Radio Wave Propagation Branch of Naval Research Laboratory, Washington, D.C., where he designed and developed data handling devices for use in the analysis of radar echoes. In January, 1959, he transferred to the Radio Astronomy Branch of NRL, where he has been involved in the planning and development of a comprehensive research program in Radar Astronomy.

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Samuel Silver (M'46–SM'50–F'54) was born in Philadelphia, Pa., on February 25, 1915. He received the B.A. and M.A. degrees in physics in 1935 and 1937, respectively, from Temple University, Philadelphia, and the Ph.D. degree in physics in 1940 from the Massachusetts Institute of Technology, Cambridge.

S. Silver

Following one year as a postdoctoral research assistant in the Mendenhall Laboratory of Physics at Ohio State University, Columbus, he joined the faculty of the University of Oklahoma, Norman, where as instructor and assistant professor of physics he served until 1943. During that period, he conducted research on molecular structures. He then joined the Radiation Laboratory at M.I.T. as a staff member in the Antenna Group where he carried on research on theory of microwave antennas and networks.

He joined the newly-formed Antenna Research Branch of the Naval Research Laboratory, Washington, D.C., in 1946 as head of a basic research group. He came to the Department of Electrical Engineering of the University of California, Berkeley, in 1947 and was made Professor of Electrical Engineering in 1950 and subsequently Professor of Engineering Science. In 1956 he was appointed Director of the Electronics Research Laboratory of the Electrical Engineering Department. He developed the research program on microwave antennas and applied electromagnetic theory and related areas of microwave electronics. He is currently directly engaged in upper atmosphere studies and solar phenomena in the microwave region.

Dr. Silver is currently Chairman of the International Commission VI (Radio Waves and Circuits) and Secretary of the U.S.A. National Committee of URSI. He is a Fellow of the American Physical Society and a member of the American Geophysical Society, the New York Academy of Sciences, and Sigma Xi.

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Jerome B. Wiesner (S'36–A'40–SM'48–F'52) was born in Detroit, Mich., on May 30, 1915. He received the B.S., M.S., and Ph.D. degrees in 1937, 1938, and 1950, respectively, from the University of Michigan, Ann Arbor.

From 1940 to 1942, he was chief engineer of the Library of Congress. In 1942, he was appointed as a staff member of the Massachusetts Institute of Technology Radiation Laboratory, Cambridge, and in 1945 he joined the University of California Los Alamos Laboratory. He is now a professor of communication engineering at M.I.T., Director of the Research Laboratory of Electronics there, and a member of the staff of M.I.T.'s Lincoln Laboratory.

J. B. Wiesner

Dr. Wiesner is a member of Sigma Xi, Phi Kappa Phi, Eta Kappa Nu, Tau Beta Pi, and the Acoustical Society of America.

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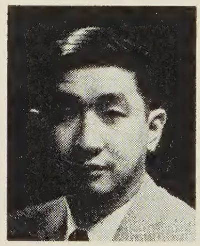
Benjamin S. Yaplee (S'46-A'50-M'55) was born in Seattle, Wash., on August 25, 1923. He received the B.S. degree in electrical engineering from the University of Washington, Seattle, in 1947.



B. S. Yaplee

He joined the Naval Research Laboratory, Washington, D.C., in 1949 and was engaged in research on radio propagation with the Wave Propagation Branch from 1949 to July 1, 1954. He then joined the Radio Astronomy Branch where he has been engaged in research on navigation problems, centimeter wave radio astronomy, and more recently in radar astronomy. He is at present head of the Radar Astronomy Section at NRL.

Mr. Yaplee is a member of RESA, Commission V of URSI and the Washington Academy of Sciences.

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